A NOVEL COLOR TV SYSTEM BASED ON SPIRAL SAMPLING OF U-V PLANE

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

by

A. ILANGOVAN

to the

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

AUGUST, 1994

CERTIFICATE

It is certified that the work contained in the thesis entitled "**A Novel** color TV system based on spiral sampling of U-V plane", by *A. Ilangovan*, has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

Dr. S.K. Mullick

Professor

Dr. Sumana Gupta

Assistant Professor

Department of Electrical Engineering

Indian Institute of Technology

Kanpur, India

August, 1994

ABSTRACT

The redundant color information for the eye, in the existing method of color representation for Video/Television system, is identified. The peculiarities of the color plane (spanned by U and V signals) are studied in depth, and the two signals are combined into single signal by spiral scanning approximation, which is similar to 2-D quantization. The "Bandwidth" and the "Color signal approximation noise ratio" are derived for the new signal. For ameliorating the noise problems, squaring and scrambling operations are also developed.

The experiments prove the validity of such an approximation, with very few encirclements (6) of the spiral. While band limiting the new signal, the quality deteriorates considerably. To improve matters, the spiral is made to vary along Y - the luminance axis, according to the varying nature of colorgamut.betterscrambler also is developed and the net result is a reasonable quality of images with single chroma signal and luminance signal (Y). For the purposes of data transmission, the new signal requires only 5 bits for quantization to provide excellent quality, whereas the original two signals (U and V) required totally 8 bits (4 bits each).

DEDICATED

TO

ALL INDIA RADIO

AND

DOORDARSHAN

ACKNOWLEDGEMENTS

I would like to express my very sincere and deep gratitude towards my guides Dr. S.K. Mullick and Dr. Sumana Gupta, for their constant encouragement, co-operation, guidance and their understanding in permitting me to choose the work of my interest and letting me the freedom throughout the project.

Next to them, I wish to thank Dr. AbaiKumar, for his constant encouragement right from my UG course.

If I can dedicate my thesis twice, next to AIR/DD, I would like to do so for all my friends, throughout the life. They were all, "all" for me. Particularly, my survival in this institute as a student could be possible only because of Arumugam, Guru Prem Prasad and Srinivasan. They have really saved me, while I was drowning. My special thanks are also due to Vivekanand Samiti and their members, Swami Nathan and Kalee Prasad.

During the project work, I have troubled everybody, whoever I can, and deeply putforth my gratitude for all of them. My Special thanks are due to Dr. P.R.K. Rao who gave me the courage to do some derivations. I also thank Dr. Karunakaran (CAD Dept.), Dr. Karnick (CS Dept.) and Dr. Ramesh (Mech. Dept.) for their kindness to permit me to use their laboratories for obtaining images. I also thank Mr. Ashish Kelkar, Mr. DurgaPrasad and Mr. K.N. Sharma who have helped me a lot in this connection. Thanks are due to Mr.Prasanth and Mr. Kumar for their kind cooperation whenever needed. Thanks to Mr. Ranganathan for given me many of his programms to start the project. Thanks to Mr. Krishna Moorthy for his help in filter design and discussions. Also I thank Mr. Ashish Jadav for his suggestions.

I have really enjoyed, while simulating the number of experiments in the computer systems and I sincerely bow my head to "all the contributors for computer invention" and specially to the modern temple - "The Computer Centre" of IIT, Kanpur.

I also thank and happily recall the memorable times I have spent with all my friends at IIT, Kanpur : Malli, Krishna Moorthy, Kasi, Immi, Pandimani, Ilango, Punns, Justin, Padmanaban, Rajesh, Murali, Venki, Ravi, Palani, Raghu, Uma Mahesh, Solai, Ramesh Chandran, Guru, Nari, Jaisankar, Vivek, Dhans, Jeyaraj, Kumaresh, Devaram, Varadan, Palanivel and Srikanth of Hall-4 and friends of Doordarshan, especially Mr. Thiagarajan, Mr. Navaneetha Krishnan, Mr. Anantha Krishnan, Mr. Sairam (and mother), Mr. Sebastian and Mr. Kalidoss.

Also, I remember specially all my AIR, Madurai friends. I always considered myself as a representative of all of them to do this work.

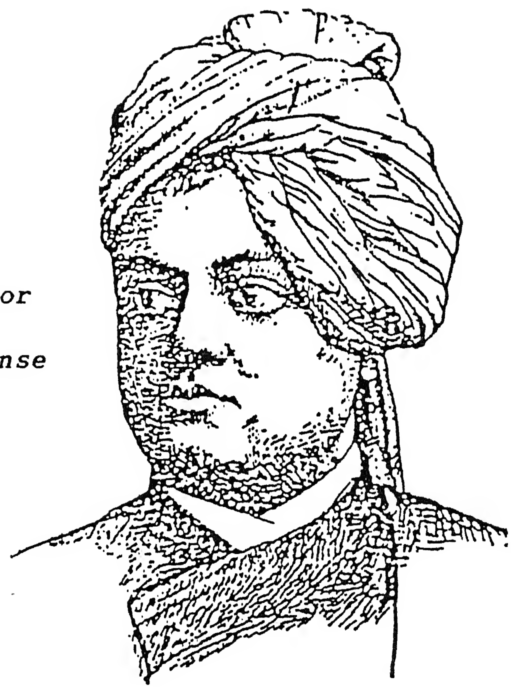
Finally, I would like to thank all my loving family members, specialy my dear little angel baby Abinaya, for their love, care, patience, understanding and letting me totally free from the family responsibilities.

Also, to Doordarshan once again. Though I have dedicated this thesis to AIR/TV, I feel it is still not sufficient because after all without my department, I am no where.

I also thank Mr. J.P. Gupta for the neat and fast typing of thesis and Mr. Dinanath (Photo Point, IIT Gate) for his kind co-operation, to take slides/photographs.

" So long as the millions live in hunger and ignorance, I hold every man a traitor who, having been educated at their expense pays not the least heed to them!"

- Swami Vivekananda



CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PHOTO PLATES

CHAPTER - 1

COLORS ARE THE SMILES OF THE NATURE
-Leigh Hunt

INTRODUCTION

"*COLOR*" plays an important role in every walk of life. The silvery snow capped mountain, trees with colorful flowers, the colorful singing birds, the magical rainbow etc.., bring peace and give pleasure in life. Color is a measure in many cases like, the ripeness of fruits, and in chemical laboratories etc. In industries, offices and in homes, color plays a predominant role. The love for color in human beings is reflected in colorful dresses. In short, life without color would be quite dull.

1.1 FUNDAMENTALS OF COLOR

1.1.1 What is Color ?

"*COLOR*" in general can be understood in three different senses [1]. In the physical sense, *COLOR*, in other words *LIGHT*, is the *VISIBLE RANGE* of spectrum extending from 400 to 700 nm wavelength, through the rainbow colors *VIBGYOR*.

The various possibilities of spectral power distribution in the visible range implies various colors, and the count of colors is infinite. However, there are many combinations of spectral energy which will stimulate the same sensation, and thus be indistinguishable to the eye. Almost all the colors of the visible spectrum can be matched to the eye, by a combination of 3 chosen colors called *Primaries*. The experimental set up for such matching is shown in Fig. 1.1.

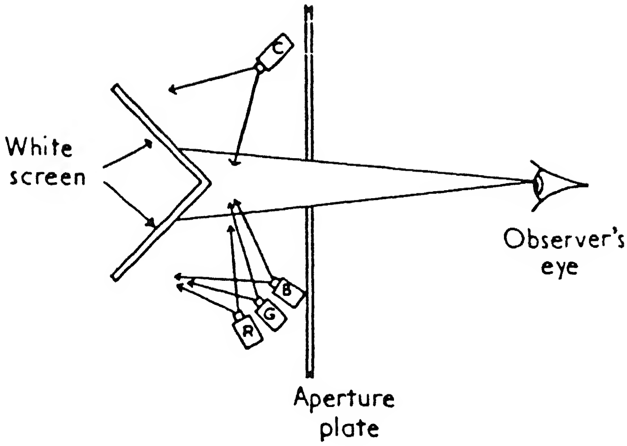


Fig 1.1 The principle of trichromatic matching. The upper white screen is illuminated only by light of the test color C. The lower white screen is illuminated only by a mixture of red, green, and blue light from the three projectors R, G, and B. By adjusting the amounts of red, green and blue light in the mixture, it can be made identical in appearance to the color C. [4]

The choice of primaries should be in such a way that, no two primaries can combine to match the third primary. Hence it turns out that, two primaries at the ends of the spectrum, and the third at the middle of the spectrum, leads to the choice of Red, Green and Blue primaries.

However for the choice of primaries any particular wavelength around the respective R,G,B color regions is not important because the ratio of proportions among these primaries alters accordingly to the color being matched. But the total range of possible colors that can be reproduced (COLOR GAMUT) are decided upon by the choice of primaries only.

The amount of these primaries for any color match are known as *TRISTIMULUS VALUES*, and the art of measuring color is known as *COLORIMETRY*. The standards of colorimetry and other related information is available in [2].

1.1.2 Specifying Color

The choice of physical primaries,to match the unit power of each wavelength of the spectrum can be not only positive but also negative. Refer Fig. 1.2.

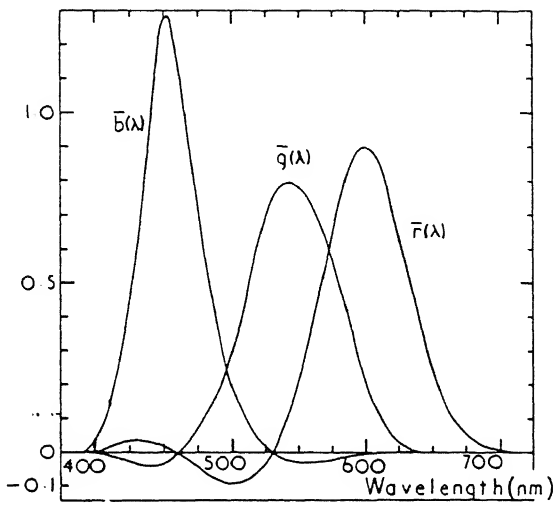


Fig 1.2 Color matching functions showing the amounts $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, and $\bar{b}(\lambda)$ of red, green, and blue light required to match unit power of each wavelength of the spectrum, using matching stimuli of wavelengths 650, 530, and 460 nm respectively[4].

The negative color means the removal of that primary color by the same amount (In color matching experiments as in Fig. 1.1, this is possible by adding the respective primary with the actual color being matched.). In any actual color reproduction system, removal of a color i.e. negative value for a primary color is impossible.

Hence the total colors which are reproducible are always less than the actual color ranges, and the reproducible color ranges are decided by the choice of primaries. However, with a suitable choice of primaries, the normal color range can be fully covered. But for the purpose of objective color specifications of all spectral colors, we need non-physical primaries.

Non-physical implies that, the primaries also lie outside the visible range in the spectrum [1]. Such a choice led to XYZ system, which has only positive values for the entire visible spectrum. Refer Fig. 1.3.

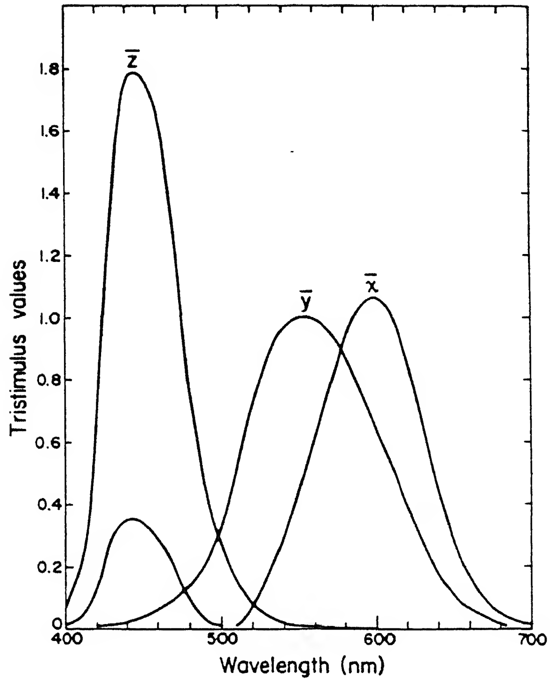


Fig 1.3 Color matching functions for X, Y, Z. Tristimulus values per watt of indicated wavelengths, for CIE 1931 standard observer.[1]

The International Commission on Illumination (CIE) has standardized the XYZ system for color specifications. Hence, any color can be uniquely specified with X,Y,Z values. However, as one can observe, the given color point is in the three dimensional (X,Y,Z) system, which is difficult to handle. Care is taken, in the system evaluation in such a way that, the choice of primary Y is similar to that of the relative luminosity of human eye throughout the visible spectrum. In other words, the Y primary is nothing but the black and white component of any color under consideration. Therefore, one can conveniently handle x,y,z instead of X,Y,Z, where x and y are known as *chromaticity components* and are defined as

$$x = \frac{X}{X+Y+Z}, \qquad y = \frac{Y}{X+Y+Z} \tag{1.1}$$

Therefore, the colors can now be specified by the chromaticity values, x and y which can be viewed in a two dimensional plot easily, and Y value is also additionally specified.

The chromaticity diagram [3], shown in Fig. 1.4 (with x and y chosen as the x and y axes) gives all the spectral colors ranging from 380 nm to 780 nm, with different color regions. The CIE/FCC (Federal Communication Commission) primaries are also shown in the same figure.

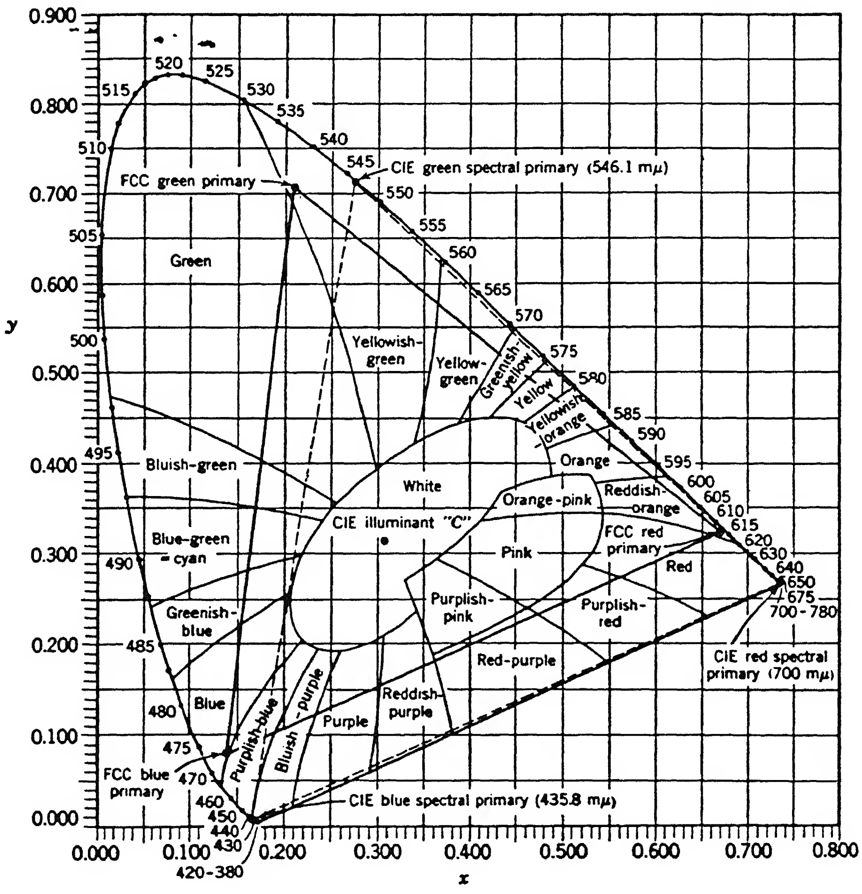


Fig 1.4 Chromaticity diagram with color designations of various areas. [3]

1.2 COLOR FOR TELEVISION

1.2.1 Choice of Primaries

As mentioned in 1.1.1, the particular choice of primaries in the Red, Blue and Green regions determines the range of reproducible colors.

In Fig. 1.4, the color gamut for FCC and CIE primaries are shown as

triangles connected by the respective primary points in the chromaticity diagram. In order to cover more colors, we are tempted to move the primaries to the corners, in order to enable the triangle to cover maximum colors. But there are other related problems, concerning the luminous efficiency i.e. ability to produce reasonable brightness with the given power. It is not possible to manufacture CRT phosphors with high excitation purities which at the same time, have sufficient luminous efficiency [5]. Taking this into consideration, the FCC primaries are chosen for color television system[3].

1.2.2 Missing Colors

Obviously, colors outside the triangle (RGB) of primaries cannot be reproduced. For example, referring to Fig. 1.2, to match the wavelength at 500 nm, negative value for red primary is needed, and this color point in the chromaticity diagram is shown as `K' in the Fig. 1.5. However, such a negative amount is impossible in the reproduction mechanism. Therefore, with the amount of other primaries needed for making 500 nm `K' point, the actual color reproduced will be point `F' on the line connecting `K' and `R'.

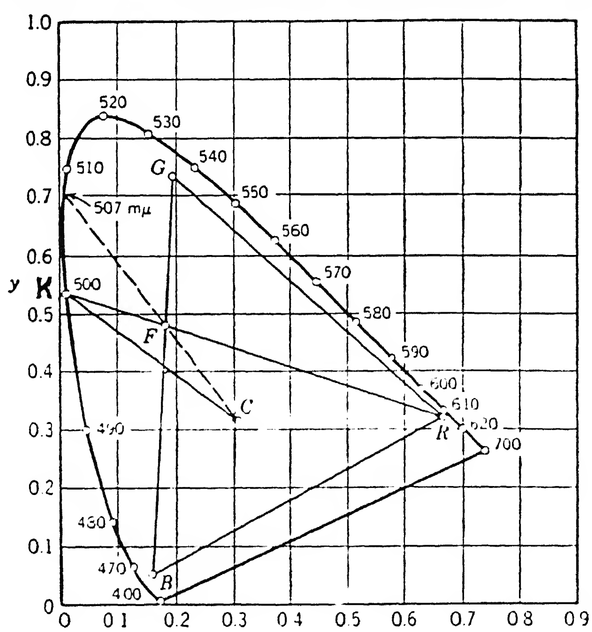


Fig 1.5 The projection rule for pure spectral color regions within chosen primaries. [3]

Also we can observe that, point `F' lies on the line connecting the `B' and `G' i.e. Blue and Green primaries. It implies that, along the direction $\overrightarrow{RK}$, the maximum amount of reproducible color is `F' only, without the negative amount of red primary.

In this sense, all the colors lying outside the color gamut are projected upon the maximum possible color points, with some change in dominant wavelength. In this case, the change is from 500nm to 507nm as shown in Fig.1.5, with respect to the reference white point `C'.

1.2.3 JND'S of Chromaticity

JUST NOTICEABLE DIFFERENCE (JND) is another important concept in the color studies. Referring to the experimental set up in Fig. 1.1, once again we try to match colors. But here the color being matched is not the outer spectral color, and is any arbitrary color with some x,y,z value. Such a color is projected on one side of the viewing field and is known as reference color point. On the other side, with another set of adjustments for primary colors,

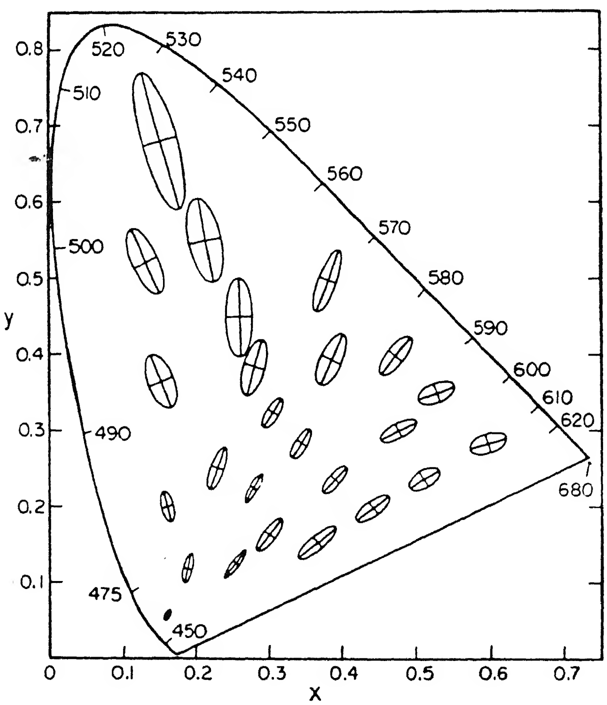


Fig 1.6 JND ellipses for 25 chosen colors in chromaticity diagram (Ellipses 10 times enlarged) [1]

initially we set them with the same x,y,z values of the color being matched, and then in all the angles (along the chromaticity diagram) the color point is moved until the "just noticeable difference" in color is perceived. For any chosen reference color point, such JND points form an ellipse according to D.L. Macadam [6], He had conducted elaborate experiments, and for 25 selected reference points, he drew the JND ellipses. Refer Fig. 1.6. Also he had given the method to get such approximate JND ellipses, for any reference color point on the chromaticity diagram [7].

1.2.4 Important Colors

The very important colors and the most frequently occurring colors are the colors of human skin, soil, sky, green foliage etc. and they are around the reference white color point. Therefore they are very well covered by the primaries. With reference to the JND, and Fig. 1.6, one can see that the missing color ranges have longer JND ellipses implying that though missing area of the colors is big, the actual missing color ranges are small and also these colors around dark green and magenta colors below the red-blue connecting line are unnatural and less common in occurrence. Therefore, the choice of primaries is well justified.

1.2.5 Transmission Primaries

From the primaries, R,G and B, the transmission primaries Y, U and V are also developed where Y is nothing but luminance (black and white) contribution of the original primaries R, G and B given by

$$Y = 0.299\ R + 0.587\ G + 0.114\ B \qquad (1.2)$$

The other two transmission primaries U and V are nothing but B-Y and R-Y respectively and are also known as chrominance signals. They are

$$U = -0.299\ R - 0.587\ G + 0.889\ B \tag{1.3}$$

$$V = 0.701\ R - 0.587\ G - 0.114\ B \tag{1.4}$$

For achromatic colors i.e. when all the three colors are in equal amount, say `C', the Y value also will be equal to `C' and U, V will be equal to zero.

Such transmission primaries have very important advantages over the original primaries [5].

1. The bandwidth required for the Y, U, V signals are less than that of the R,G,B signals for the same quality of picture. Particularly very large bandwidth reduction for U and V signals is possible.
2. Also, the noise immunity is more for the transmission primaries than that of the actual primaries. Hence for television broadcasting purposes, invariably only the transmission primaries are used.

1.3 THE BASIC QUESTIONS ON COLOR

1.3.1 Primaries and Approximations

As mentioned in 1.1.1, by means of the three primaries system, we reproduce the color which only has the same color sensation as actual color for the eye, but spectrally different color. Hence fundamentally, we deal with the equivalent colors only, and not with actual colors. Therefore question arises naturally as to what extent such approximations can be carried ? And when this is done, will it give rise to any system simplification? Also a system based on primaries clearly reveals that not all possible colors due to different spectral distributions, need be reproduced and the reproducible colors with 3 primaries system are sufficient.

1.3.2 Metamerism

Two entirely different spectral powers as shown in Fig. 1.7, can have identical color sensation for the eye [4]. Such phenomenon is known as *metamerism*, and such stimuli, which are spectrally different but visually identical, are known as *metamers*. Strictly speaking, for any given spectral power distribution, many other different spectral power distributions but with the same color sensation can be found [3]. The question here is, whether such metamers mean only the primaries approximation as in 1.3.1, or something other than that? And if it is something different, what is it?

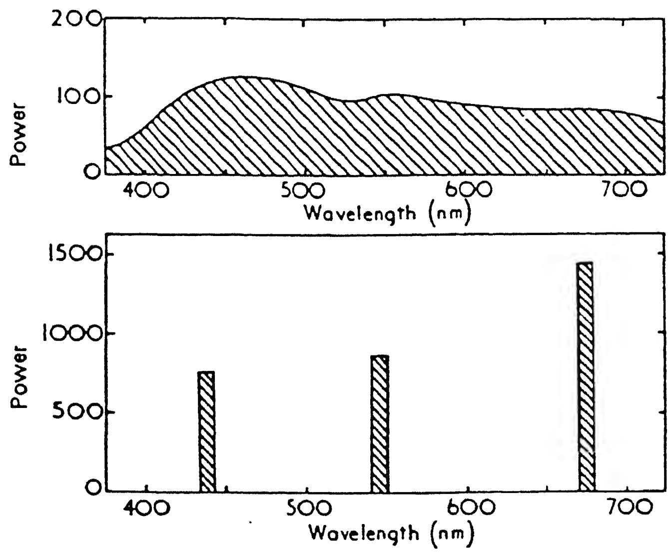


Fig 1.7 The upper curve shows the spectral power distribution of a white light; the power distribution shown in the lower diagram refers to a light which, to the eye, appears exactly the same color. (Note the different power scales used)[4].

1.3.3 Land's Two Primaries System

With reference to the works of E.H. Land [8], he claims that only two primaries are sufficient with 585 nm as the center.One primary above 585 nm wavelengths (which he calls long record) and other one below 585 nm (short record), are used in taking the two photographs of the same scene.While projecting back, the long record is projected through red filter, and short

record without any filter. With such an arrangement Land claims that, all colors can be reproduced. Though there were very serious comments on Land's work, Land's demonstrations cannot be ignored, and it still remains a question as Land puts in his own words - "the addition of a third stimulus does enrich the colors somewhat but we do not know whether what is missing is due to inadequacy of technique or to the need of a little help from a third stimulus?"

1.3.4 Complementary Colors and White

Referring to the chromaticity diagram in Fig. 1.4 again the white color point can be matched with any two properly mixed color points (complementary pair) whose connecting line passes through the white color point. As is obvious, there can be infinite such combinations. Also, as in the three primaries system, with suitable mixture of these primaries, we can get white color. Again choice of primaries are less important, and infinite primary choices are possible.

Likewise with any number of different color points, we can get the white color [9]. Therefore naturally again the question arises as to, what is the actual white color?

1.3.5 JND

As mentioned in 1.2.3, the concept of JND, puts a very big question as to when a reference color point, and all the color points lying within the JND ellipses, cannot be distinguished by the eye visually, why should we bother to preserve or transmit such less informative signals? And how to exploit these redundancies?

1.4 THE PRESENT WORK

In the quest for finding answers to the questions above, one may consider two approaches.

1. As Land had proceeded, one can break away from the basic infrastructure and ask questions at the fundamental levels

(or)

2. Within the infrastructure built for color i.e. colorimetry, primaries, transmission primaries etc., one may try to find the answers.

The present work takes the second approach, and tries to find some methodology for exploiting the redundancies.

In this scheme of things, the redundant color points around any chosen color points are approximated. An operation equivalent to two dimensional quantization is carried out on the two chrominance signals U and V, to combine them into a single signal. Therefore unlike the present practice of storing/sending three signals Y, U and V, it is sufficient to handle only Y and X, where X is the new signal obtained by combining U and V signals.

1.5 LAYOUT OF THESIS

In chapter 2 the important properties of the color plane are reported. Based on these properties, the proposed spiral approximation to obtain single new signal, by combining the two chroma signals U and V is given in chapter3. Also given are the analysis for L value (no. of encirclements of the spiral), bandwidth, noise, CSANR, and additional SNR burden and squaring/scrambling operations for the new signal. Chapter 4 reports the experimental details with results including photoplates. The varying spiral, saturation scrambler and the efficient data coding possibilities for the new signal are also reported in this chapter. Finally chapter 5 concludes with the observations/explanations and also with suggestions for further work.

CHAPTER - 2

THE COLOR PLANE

Among the transmission primaries Y, U and V, the space spanned by the two chrominance signals U and V is known as color plane. Such a color plane is shown in Fig. 2.1, in which the third signal Y lies on the z-axis (piercing through the paper), and can be neglected here for further discussions.

2.1 PROPERTIES OF COLOR PLANE

The color plane possess very important properties, unlike the chromaticity diagram. It can be observed that the the complementary pairs (Blue-Yellow, Red-Cyan, and Green-Magenta) fall exactly at 180° out of phase and the entire color plane is nearly split into six equal regions, between two adjacent major color lines like Blue-Magenta, Magenta-Red etc.

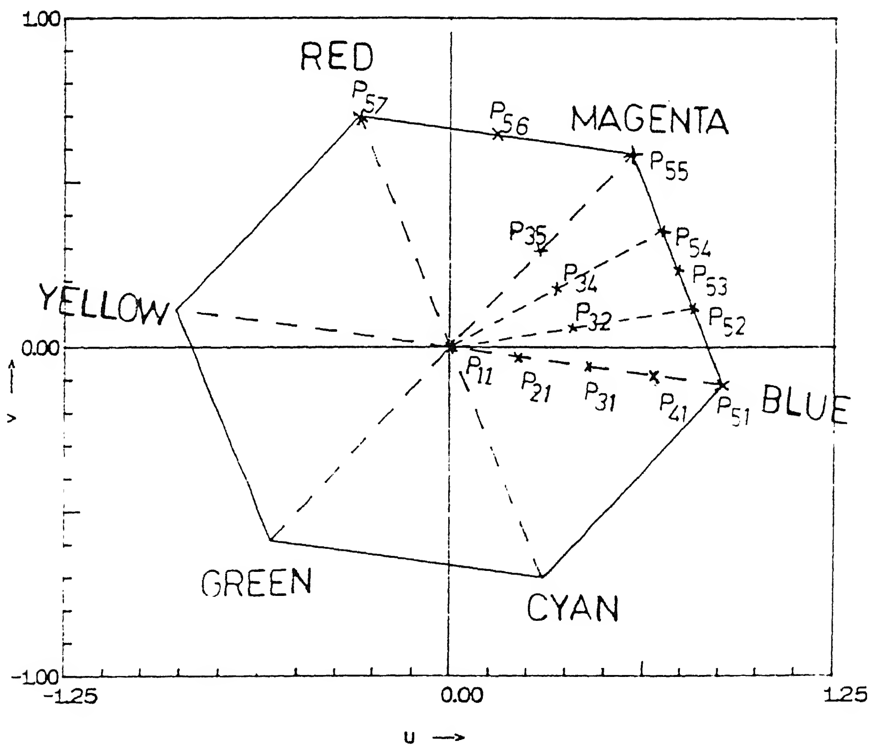


Fig.2.1 Color Plane

2.1.1 Behavior along Radius

For any chosen angle, the change in the primary colors for that angle is linear and systematic. To explain this behavior, we consider the case of the blue color line, and choose the points at 0%, 25%, 50%, 75% and 100% radii designated by P_{11}, P_{21}, P_{31}, P_{41} and P_{51} respectively in Fig. 2.1

For all the calculations, we assume Y = 0.5. The 100% pure blue color point P_{51} is given by U = 0.886, V = -0.114. For other points P_{11} to P_{41}, percentage of the radius along the blue line is taken and the values for U and V are obtained.

By transformation, we can get R, G, B components from Y, U, V values [refer Appendix-A]. These values are listed in Table-1 shown below.

TABLE 1

Per-centage	Points	Y	U	V	R	G	B	Min. (R,G,B)	R′	G′	B′
0%	P_{11}	0.5	0.0	0.0	0.5	0.5	0.5	0.5	0.0	0.0	0.0
25%	P_{21}	0.5	.2215	-.0285	.4715	.4715	.7215	.4715	0.0	0.0	.25
50%	P_{31}	0.5	.443	-.057	.443	.443	.943	.443	0.0	0.0	.5
75%	P_{41}	0.5	.6645	-.0855	.4145	.4145	1.1645	.4145	0.0	0.0	.75
100%	P_{51}	0.5	.886	-.114	.386	.386	1.386	.386	0.0	0.0	1.0

In the actual system, the range of primary colors are allowed to have the values from 0.0 to 1.0 only. However, for the sake of completion of the example, we ignore the excess blue color for points P_{41} and P_{51}.

In the table, we also see min(R,G,B) and R′,G′,B′ columns. As the name implies, the min(R,G,B) is the minimum value among the R,G,B values. We also define

$$\left.\begin{aligned} R' &= R - \min(R,G,B) \\ G' &= G - \min(R,G,B) \\ B' &= B - \min(R,G,B) \end{aligned}\right\} \qquad (2.1)$$

As we can observe from the table, for point P_{11}, the U and V values equal zero and the point is actually on the origin (achromatic point). The min(R,G,B) value is equal to 0.5, which is the value for `Y' also. In other words, min(R,G,B) is the quantity, which exists for all the colors, and contributes only to the Y value along that axis of the color plane.

The remaining color quantities span the color plane and are given by the R′, G′and B′. These are obtained by subtracting the min (R,G,B) (the quantity which contributes only to the Y value) from R,G,B values.

Therefore, now considering the R′, G′, B′ values as given in Table-1, only the B′ changes linearly as the percentage of radius changes. Similarly, in the other directions also, the changes along the radii are linear. However, the ratio among R′, G′, B′ changes with angle. This is discussed below.

2.1.2 Behavior along Phase Angle

Strictly speaking, here we are not studying the behavior along phase angle. However it can be approximately taken as phase angle behavior in the modified color plane (dealt later).

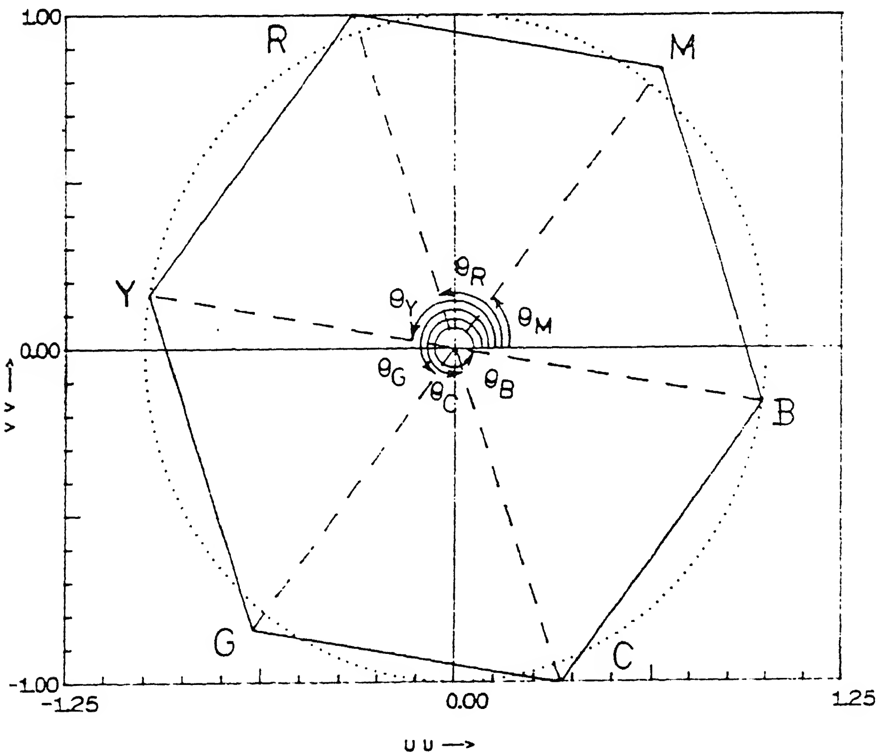
Points P_{51} and P_{55} are the pure blue and magenta colors respectively. The distance between these two points is split into three equal parts, and we get the points P_{52} and P_{54} as shown in Fig. 2.1. For convenience we would like to handle half radii points in the respective directions. These are shown by the points P_{31}, P_{32}, P_{34} and P_{35}.

Once again, keeping the Y value fixed at 0.5, for the U and V values of these points, we find R′, G′, B′ values which are listed in Table-2 below.

TABLE 2

Points	Y	U	V	R	G	B	Min (R,G,B)	R′	G′	B′
P_{31}	0.5	0.443	-0.057	0.443	0.443	0.943	0.443	0/6	0.0	0.5
P_{32}	0.5	0.393	0.06	0.560	0.393	0.893	0.393	1/6	0.0	0.5
P_{34}	0.5	0.343	0.177	0.677	0.343	0.843	0.3435	2/6	0.0	0.5
P_{35}	0.5	0.293	0.293	0.793	0.293	0.793	0.2935	3/6	0.0	0.5

We observe that G′ and B′ remains constant at 0.0 and 0.5, while R′ changes linearly from 0.0 to 0.5. Such a behavior can be considered as the behavior due to phase angle, since the radii are almost same in all direction of the modified color plane, to be discussed in the next section.



θ_M = 52.125°
θ_R = 108.353°
θ_Y = 170.607°
θ_G = 232.125°
θ_C = 288.353°
θ_B = 350.607°

Fig.2.2 Modified color plane

2.1.3 Modified Color Plane

Not only in the color regions bounded by blue and magenta lines, but for the entire plane, we would like to approximate the above behavior with respect to the phase angle. To accomplish this, we enlarge the area with constants along U and V axes respectively by 1.1111 and 1.42857 to make the radius approximately equal to 1.0 in all the directions. The reason for the choice of radius 1.0 will be given later. Hence the area of the modified color plane can be said to be equivalent to that of the unit circle as shown in Fig.2.2.

The x and y axes of modified color plane are referred to as UU and VV axes. The necessary transformations in UU, VV plane from RGB system and to RGB system are given in Appendix-1. In this plane, the above mentioned behavior can be treated as the behavior along the phase angle.

2.1.4 Color Regions

We can further observe the behavior of R′, G′, B′ signals along the periphery of the modified color plane as shown in Fig. 2.3.

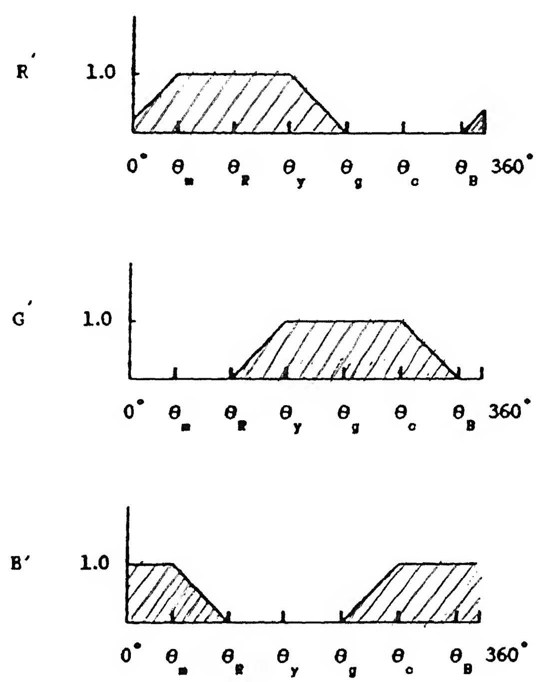


Fig.2.3 R', G', B' color regions along the phase angle

Fig. 2.3 shows the R′ G′, B′ values for maximum radius i.e. approximately equal to 1.0 for all the phase angles. For other radii values less than 1.0, the nature of R′, G′, B′ curves remain same as in Fig. 2.3 except that they are scaled by the radius value. Therefore from the observations made in earlier and present sections, we can conclude that,

a) Only two quantities among R′, G′, B′ exist for any phase angle; (refer Fig. 2.3).

b) Among the existing two quantities, one of them is at it's maximum value i.e. 1.0, and the other has a particular ratio depending on the angle. This can be seen in Fig. 2.3.

c) The above two properties are true for maximum radius i.e. 1.0. For the lesser radii also, these properties hold but the R′, G′, B′ values need to be scaled by the radius value.

2.2 THE COLOR GAMUTS

The hexagonal area in the color planes of Figs. 2.1 and 2.2 shows the full color gamut for all the Y values from 0.0 to 1.0. As already mentioned the Y signal lies on the z-axis of the color planes and the actual signal space is a three dimensional space. The color planes that we refer are the plan i.e top view of the full color space. However, along the cross section of this color space for different values of Y, we get the color gamut for that particular Y value. The shape of such gamuts varies in a regular fashion as Y varies from 0.0 to 1.0.

For different values of Y in the range of 0.0 to 1.0, the cross sectional views of the color space (which are subsets of color plane) are shown in Fig. 2.4 along with full color gamut.

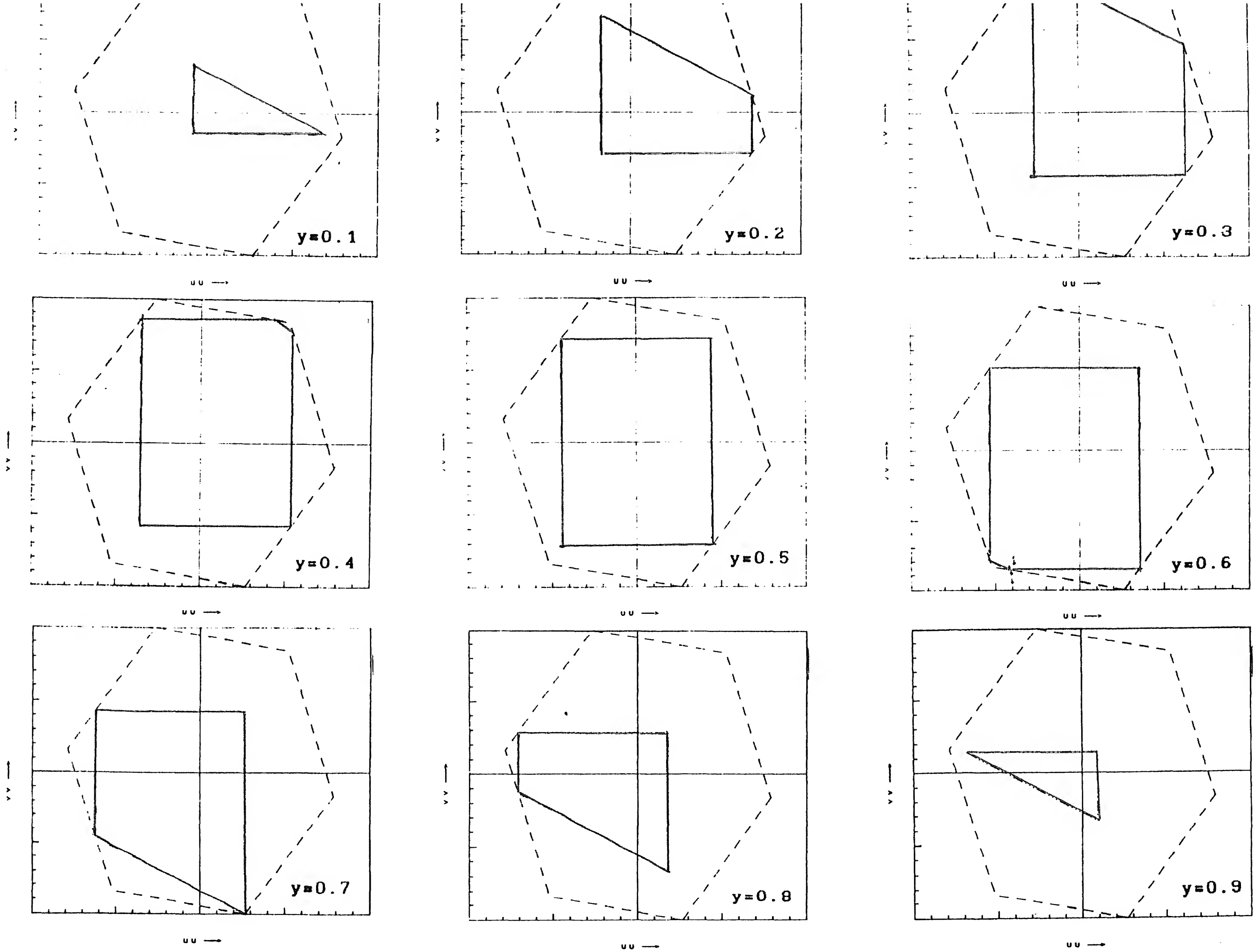


Fig 2.4 Varying color gamut for different Y values

As is evident, the actual color gamut for a given Y value is asubset of the full color gamut and manifests as different polygonal shapes. The varying color gamuts' area are limited by the normalized signal ranges of the primary colors R,G,B. Therefore for a given Y value, a color point which lies outside the varying color gamut of that Y value, implies either under flow (or) overflow of the signal range of any one of the primary colors.

Even a three dimensional diagram of the varying color gamuts for all Y values, cannot furnish full details because it would hide the nature of variation of color gamut of the rear side. Therefore, the cross sectional views along the major colors (red, cyan, blue, yellow, green, magenta) of the color plane is shown in Fig. 2.5.

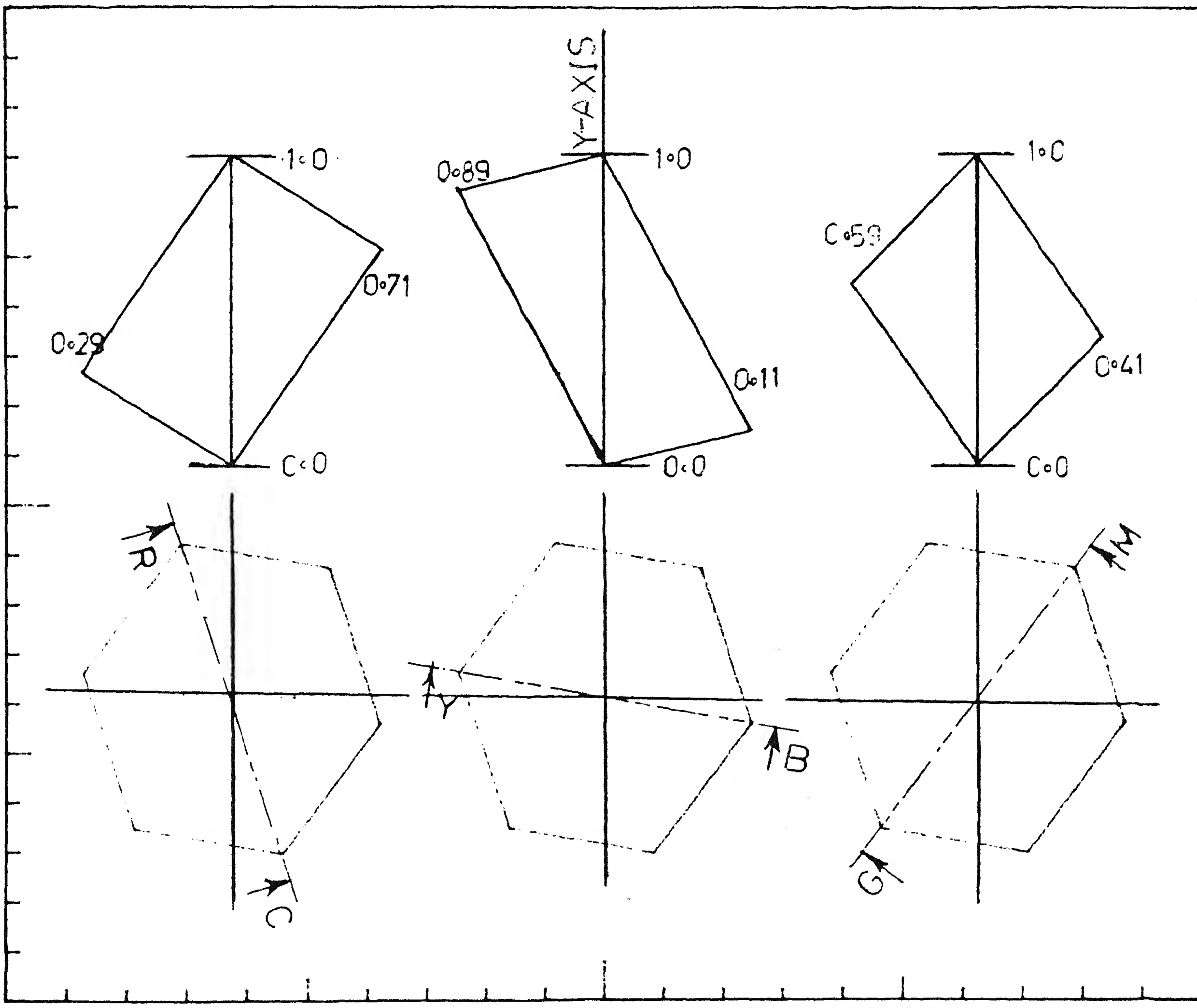


Fig.2.5 Cross sectional views of varying color gamut along primary colors in color plane.

2.3 LUMINANCE, HUE AND SATURATION [10]

2.3.1 Luminance

As already mentioned in section 2.1.1, the Y signal gives the luminance or light intensity as perceived by the eye, regardless of the color of the object seen. The contribution of the primary colors for obtaining Y is given by

$$Y = (0.299)R + (0.587)G + (0.114)B$$

Also, this Y signal lies at the origin of the color plane, (both original and modified) as already mentioned.

2.3.2 Hue

This is the predominant spectral color of the received light. The color of any object is distinguished by its hue or tint, like red, green, blue, brown, orange, yellow, purple and so on. The spectrum of such colors lies along different phase angles of the color planes. In other words, hue is another name for the phase angle of the color plane.

2.3.3 Saturation

When a pure spectral color (say green) is mixed with white color, the color of the mixture will be less in purity (less green) compared to the actual green color, but at the same time the brightness Y of the mixture increases. The study of such experiments on color planes reveals that the purest colors have the maximum radius (1.0, in case of modified color plane), and when white is mixed the radius in the color planes decreases i.e. the purity of the color decreases. In other words, the radius is the measure of saturation and the full saturated color has no white component.

2.4 THE COLOR SEEN AND THE ACTUAL COLOR

In all the color reproducing mechanisms like television, photography, printing etc, there are alwaysdifferences in the reproduced color and the actual color, due to many reasons which are briefly dealt in the following.

2.4.1 Color Control in Televisions

Among the many controls given in the TV receivers, we have the color control as well. By adjusting this, we alter nothing but the vector length i.e. radius (equivalently the length of the saturation vector) in the color plane. It is evident that when we fully minimize the color control, we see the black and white pictures, implying the radius of the vector equals zero.

2.4.2 Chromatic Adaptation

The television is viewed under different illumination conditions, like daylight, tubelight etc. In such a situation, we disregard the luminance but are particular about the chrominance change. Though we refer to the sunlight and tubelight as being white, spectrally they are very different and this fact can be realized when we look at some colored dress in these different lights and perceive them as having different colors. This phenomena is known as chromatic adaptation [1].

Hence, depending on the lighting conditions of the room, our eye chromatically adopts and in fact we actually see slightly different colors than the original colors. This effect not only alters the radius but also the phase angle of the vectors in the color plane.

2.4.3 Color Differences

Due to the above and other reasons, even though when the colors seen are slightly different than the actual colors, such differences are tolerable for normal viewing. There are many studies on color differences which include JND and many other concepts [1,4,9]. All the authors agree that the variation from the actual color around the neighborhood of it, is tolerable. Also various studies/ experiments were conducted to find the extent to which such tolerations are acceptable, and how the toleration behavior changes over the entire chromaticity diagram etc. But how to effectively use these redundancies for the present day tasks of bandwidth compression, source/channel coding etc. remains an unanswered question!!

CHAPTER - 3

THE PROPOSED APPROACH FOR COMBINING THE SIGNALS

In this thesis, an attempt is made to combine the two chrominance signals U and V, that would lead to efficient resource utilization.In other words, the aim is to achieve compression/data rate reduction by using a different approach. The two chrominance signals jointly enjoy many good and similar properties needed for the approximations in the color plane. This is discussed in sections 2.1 and 2.3.

3.1 SPIRAL APPROXIMATION ON COLOR PLANE

Referring to sections 2.1.1, 2.1.2 and 2.1.4 we observe that when the radius in the color plane changes, *saturation* of the color alters. However, when the phase angle is changes, the *hue* of the color also changes. In other words, the change in pure blue color (fully saturated) into less pure blue color (less saturated), implies a change in radius. Similarly, change of say, pure blue color into another color i.e. a mixture of blue and red colors means a phase angle change.

It is a fact of human visual perception that, a change in the vector length (saturation) is more tolerable than the change in the phase angle (hue).

Based on this idea, the points in the entire color plane are mapped onto points on a spiral curve in the same color plane as shown in Fig. 3.1. For the spiral to cover all the color points, we use the modified color plane. Henceforth by "color plane" we mean the modified color plane only.

As shown in Fig. 3.1, the radius of the spiral starts from 0.0 and goes upto 1.0, covering almost the entire color plane (Therefore the choice of

constants for converting the original color plane into a modified color plane are justified).

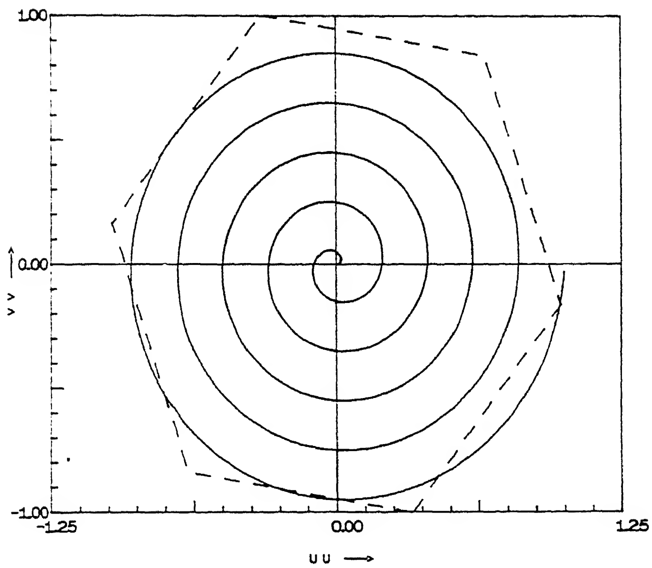


Fig.3.1 Simple spiral with L = 5 on color plane

We define `L' as the number of circles of the spiral curve. In Fig. 3.1, the `L' value used is 5. For a given `L' value, the spiral points are obtained by using the following equations.

$$UU = C \, . \, \cos(2\pi LC) \tag{3.1}$$

$$VV = C \, . \, \sin(2\pi LC) \tag{3.2}$$

where C is the new signal obtained by combining UU and VV signals. The range of C also is normalized i.e. from 0.0 to 1.0.

3.1.1 The Spiral Mapping

To explain the nature of mapping of color points onto spiral points, a small portion of Fig. 3.1 is shown enlarged in Fig. 3.2. The center line between the two adjacent spiral lines is shown by the dotted line in the same figure.

Considering the color point P_1 of Fig.3.2, the vector is extended in the same phase angle, and the point P_1 is mapped onto point `P_{1m}' (as shown in

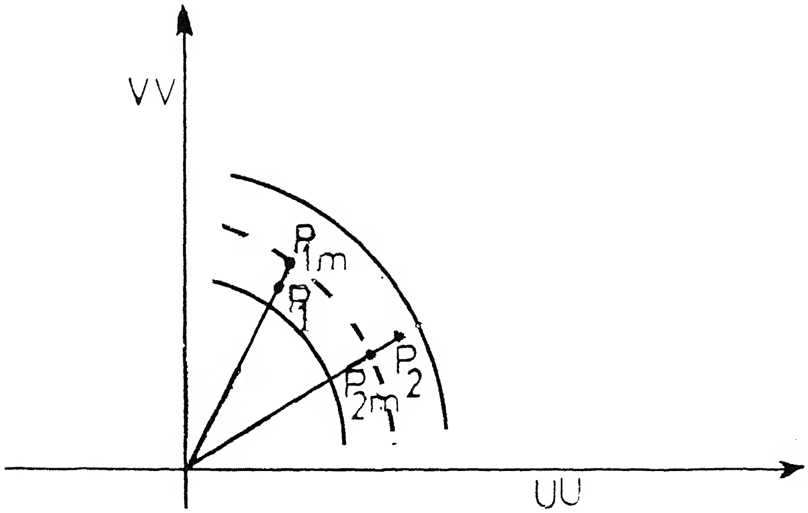


Fig.3.2 The spiral mapping

figure) from below. Similarly, while considering the color point P_2, this point is mapped onto point `P_{2m}' from above, preserving the phase angle.

In this manner, all the points in the color plane can be mapped onto the spiral points. For the outermost circle of the spiral, all the color points lying above the spiral in the respective phase angles are mapped from above.

3.1.2 The Nature of Spiral Structure

The value of any spiral point or the signal `C' is given by the radius of that point in the color plane. Therefore for a given value of `L', with C = 0.0 at the origin, the spiral point at the completion of the first circle will have the value equal to 1.0/L. i.e. C = 1.0/L. Similarly at the completion of second circle C = 2(1.0/L) and so on. Finally at the completion of the circle (Lth circle), C = L(1.0/L) = 1.0.

From the unique structure of the spiral, we find that, for any radius given, C lies in a particular phase angle only. This is illustrated by the following example.

Let $L = 5$ and $C = 0.42$,

$$C\,L = (5) \times (0.42) = 2.1$$

The point thus lies above two circles i.e. on the third circle of the spiral, and the exact phase angle is obtained by ignoring the integer part from 2.1, i.e. 2.1 - 2.0 = 0.1. It implies that the point lies at a phase angle given by,

$$(0.1) \times (360) = 36 \text{ degrees} \quad \text{(or)} \quad 10\% \text{ of } 360^{o}$$

Similarly, for a given phase angle `ϕ', it can have any one of the L values of the radii. For example

if L = 5 and $\phi = 45^{o}$, the L possible C values are,

$$C_1 = \frac{0 + (45/360)}{L} = 0.025$$

$$C_2 = \frac{1 + (45/360)}{L} = 0.225$$

$$\vdots \qquad \vdots$$

$$C_L = \frac{(L-1) + (45/360)}{L} = 0.825$$

If we look into the nature of distribution of the alphabet of the `C' signal, we observe that the alphabet is split into equal `L' parts for each completion of a circle in the spiral. This is shown in Fig. 3.3 for an assumed value of L = 5.

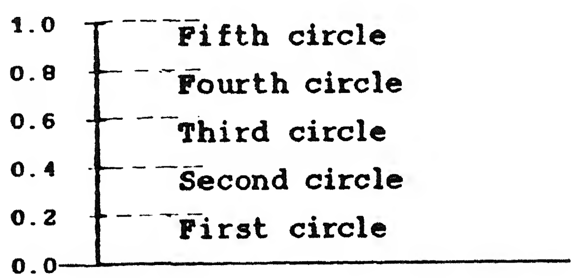


Fig.3.3 Alphabet distribution of C signal

3.1.3 Noise and Need for Squaring

The advantage of the spiral mapping is that the change of signal value due to noise, allows it to move up or down on the spiral, i.e. around the neighborhood of the actual signal. This is true for all the spiral points, except for the starting and end points. (large amount of noise/large value of L creates more problems which are dealt in later sections.) But due to the spiral mapping, the alphabet is equally distributed as shown in Fig. 3.3, whereas the actual area of the color plane covered by each circle is not equal. This leads to uneven effects due to noise. To have equal noise distribution, we first find the area covered by each circle of the spiral. For this purpose we approximate the spiral, as L concentric circles with radius equal to the maximum radius of the respective circles of the spiral.

Therefore, the area of the annular region between the two circles is given by

$$\pi(r^2 - r_p^2)$$

where r_p : radius of previous circle, and

r : radius of the circle under consideration.

For the specific case of L=5, the "area", the "normalized area" and the "progressive area total" are listed in Table-3.

TABLE - 3

L	Area	Normalized area	Progressive area total	C Value
1	0.1257	0.04	0.04	0.2
2	0.3770	0.12	0.16	0.4
3	0.6280	0.20	0.36	0.6
4	0.8800	0.28	0.64	0.8
5	1.1310	0.36	1.00	1.0

The normalized area is obtained simply by dividing the area by π as below

$$\text{Normalized area} = \frac{\pi(r^2 - r_p^2)}{\pi} = r^2 - r_p^2 \qquad (3.3)$$

The progressive total area is obtained by adding the normalized annular region areas due to all the previous circles of the spiral. The total progressive area is the squared value of `C' after the completion of the respective number of circles in the spiral. This is evident from the values given in Table-3.

The C values are also listed for this purpose. The distribution of C^2 (progressive area total) and C are shown in Fig. 3.4.

Fig.3.4 Alphabet distribution for C and C^2 (or) X signals

It may be shown easily that the C^2 value is the normalized length of spiral (from the origin), in the two dimensional space of the color plane. In other words, unlike the usual signals this new signal is formed out of two different signals such that the length of the new signal scans the two dimensional space. Hence we take the square of the signal value `C' to get the length in two dimensional space.

We refer to the squared C signal as `X'. For X signal, one can easily see that the effect of noise is uniform throughout the signal range. Hence we use only X signal for transmission.

3.1.4 Bandwidth for Signals C and X

For this purpose, once again we approximate the spiral as L concentric circles as given in the previous section. This is done for ease of derivation, without losing the essential nature of the signal. The radii for the circles here, are the average value of maximum and minimum radii of the respective circles in the spiral. Therefore we have,

$$C = \sqrt{(UU)^2 + (VV)^2} \quad \text{and} \quad X = (UU)^2 + (VV)^2 \tag{3.4}$$

Taking auto correlation of the X signal, we can write

$$\begin{aligned} E\left[X(t),\ X(p)\right] &= E\left[\left\{UU^2(t)+VV^2(t)\right\}\left\{UU^2(p)+VV^2(p)\right\}\right] \\ &= E\left[\left\{UU^2(t).UU^2(p)\right\} + \left\{UU^2(t).VV^2(p)\right\}\right. \\ &\quad \left. + \left\{VV^2(t).UU^2(p)\right\} + \left\{VV^2(t).VV^2(p)\right\}\right] \end{aligned} \tag{3.5}$$

Assuming that the processes UU(t) and VV(t) are i.i.d. processes, their cross correlation equals zero. Therefore

$$E\left[X(t),X(p)\right] = E\left[\left\{UU^2(t),UU^2(p)\right\} + \left\{VV^2(t),VV^2(p)\right\}\right] \tag{3.6}$$

Once again due to identical nature of these i.i.d. processes we can write

$$E\left[X(t),X(p)\right] = E\left[2\left\{UU^2(t),UU^2(p)\right\}\right] \quad \text{or} \quad E\left[2\left\{VV^2(t).VV^2(p)\right\}\right] \tag{3.7}$$

Assuming the processes are W.S.S. we can write,

$$R_X(\tau) = 2.R_{UU2}(\tau) = 2.R_{VV2}(\tau) \tag{3.8}$$

where $R_{UU2}(\tau)$ and $R_{VV2}(\tau)$ are the auto-correlation function of $UU^2(t)$ and $VV^2(t)$ processes.

Taking Fourier transform we get,

$$S_X(f) = 2.S_{UU2}(f) \quad \text{or} \quad 2.S_{VV2}(f) \tag{3.9}$$

where,

$S_X(f)$: spectrum of X signal

$S_{UU2}(f)$: spectrum of UU^2 signal and

$S_{VV2}(f)$: spectrum of VV^2 signal.

The spectrum of the UU^2 and VV^2 signals can be obtained by using the property that time domain multiplication is equivalent to frequency domain convolution. Therefore,

$$S_{UU2}(f) = S_{UU}(f) \otimes S_{UU}(f) \tag{3.10}$$

and

$$S_{VV2}(f) = S_{VV}(f) \otimes S_{VV}(f) \tag{3.11}$$

where,

$S_{UU}(f)$: spectrum of UU signal

$S_{VV}(f)$: spectrum of VV signal.

Since both UU(t) and VV(t) are band limited processes, and also due to the nature of the signal, the energy of $S_{UU2}(f)$ and $S_{VV}(f)$ will be concentrated more at the low frequencies. The UU^2 and VV^2 signals are also band limited, but have twice the bandwidth of UU/VV signals as shown in Fig. 3.5. Therefore, the bandwidth of X signal also is twice that of the bandwidth of UU/VV signals.

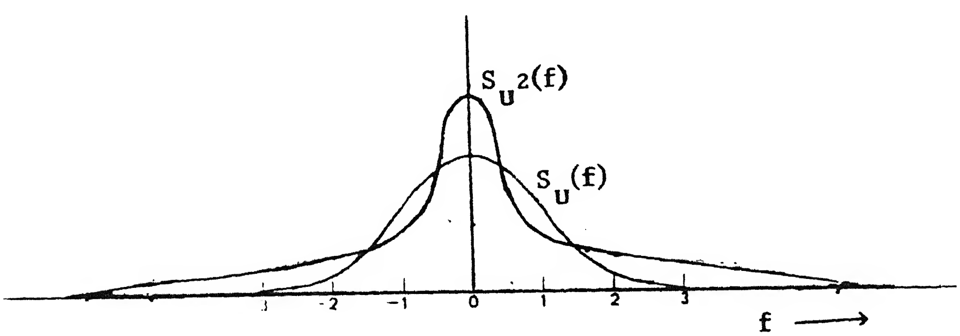


Fig.3.5 Spectral contents of U(t) and $U^2(t)$ signals [5].

Recalling that $X = C^2$ and thus $C = \sqrt{X}$, the spectrum of the `C' signal is also band limited, with

$$S_C(f) = \sqrt{2}\, S_{UU}(f) = \sqrt{2}\, S_{VV}(f) \tag{3.12}$$

However, as stated earlier, due to uniform noise effects, we use X signal for transmission and hence we require twice the bandwidth of the UU/VV signals.

But as we intend to use the bandwidth of any of the UU/VV signals only, we filter the X signal to the bandwidth of UU/VV signals. Even though such an attempt will lead to poor quality, particularly at the edges of the image, most of the information of the two signals is available in this single band limited signal, due to energy clustering around the low frequencies of the spectrum as shown in Fig. 3.5. However, if more bandwidth is affordable, then the quality can be preserved.

Another related problem here is that when L is sufficiently large, all the derivations (and expected results) hold good. But when L is small, they lead to quantization noise, as in 1-D case and filtering out in this case, can create serious problems.

The net result is that instead of handling two independent signals, we have suitably combined them into a single signal. It can result into, either system simplicity or more channel capacity.

3.2 CHOICE OF L

We know that in the tax policies of government, low amount of tax will lead to deficit budget and high amount of tax will cause the public to suffer. The choice of `L' value in our case is comparable to that of fixing the amount of tax. The lower tax case is analogous to lower L value, and the penalty in this case is, the coarse approximation of colors and hence resulting in poor reproducible color ranges. The higher tax case is analogous to higher value of L and will lead to more additional SNR burden. Hence the L

value must be chosen very carefully. The factors influencing this choice are dealt in following sections.

3.2.1 Color Signal Approximation Noise Ratio (CSANR)

Akin to the sampling and quantization of any 1-D signal, here the scanning of the color plane to derive a 1-D signal from the 2-D color plane signal results in a noise component which generate to what we may call color signal approximation-noise ratio (CSANR). The CSANR increases as L is increased.

However, unlike the usual case where we increase the number of bits (therefore the number of levels in steps of 2^n), in our case we can conveniently increment the L value in integer steps.

3.2.2 The PDF for Signals

Referring back to Fig. 2.2, we recall that the dynamic range of the two signals of the color plane can be nearly approximated to the unit circle. Since all the color points of the color plane are to be given equal consideration, the joint pdf of these signals is like a cylinder as shown in Fig. 3.6. In our case, the value of `k' shown in Fig. 3.6, is equal to 1.0.

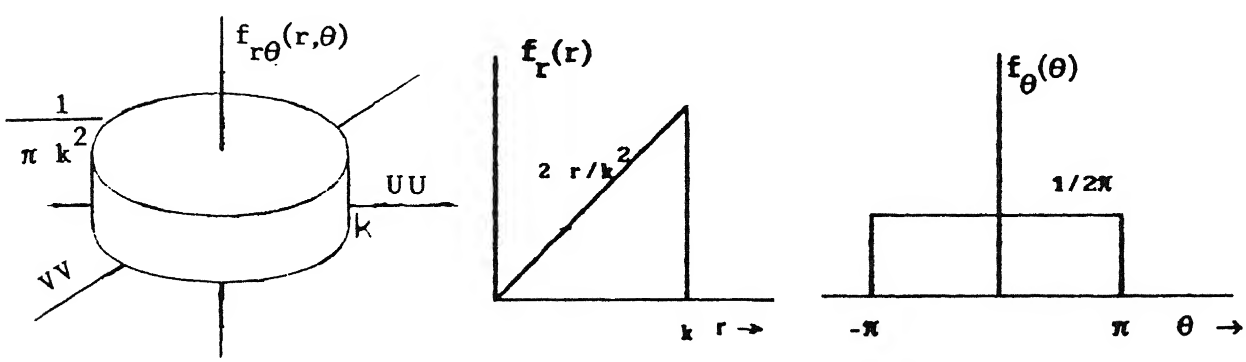


Fig.3.6 Joint and marginal probability density functions

The cylindrical joint pdf (shown in the rectangular coordinates UU and VV) along with marginal pdfs in the polar coordinates `r' and `θ' as shown in Fig. 3.6.By the standard transformation of random variables, we get

$$\iint f_{UU\ VV}(UU, VV)\, dUU\, dVV = \iint f_{r\theta}(r,\theta).r.drd\theta \qquad (3.13)$$

So, $$\iint f_{r\theta}(r,\theta)\, drd\theta = \iint \frac{1}{\pi k^2} \cdot r \cdot drd\theta \qquad (3.14)$$

The two variables `r' and `θ' are statistically independent, and therefore we can write

$$\iint f_{r\theta}(r,\theta)\, drd\theta = \int f_r(r)\, dr \cdot \int f_\theta(\theta)\, d\theta$$

$$\iint \frac{1}{\pi k^2} \cdot r \cdot drd\theta = \int f_r(r)\, dr \cdot \int f_\theta(\theta\ \ d\theta$$

$$= \int_0^k \frac{2r}{k^2}\, dr \cdot \int_{-\pi}^{\pi} \frac{1}{2\pi}\, d\theta \qquad (3.15)$$

Hence, the marginal pdfs for the radius `r' and phase angle `θ' are given by

$$f_r(r) = \begin{cases} 2r/k^2; & 0 \le r \le k \\ 0\ ; & \text{elsewhere} \end{cases} \qquad (3.16)$$

and

$$f_\theta(\theta) = \begin{cases} 1/2\pi\ ; & -\pi \le \theta \le \pi \\ 0\ ; & \text{elsewhere} \end{cases} \qquad (3.17)$$

3.2.3 PDF for Approximation Noise

As we have assumed earlier for bandwidth analysis, here also we assume the spiral as L concentric circles, for the ease of analysis without compromising the essential nature of the signal. Therefore, the process of

approximation is essentially the quantization of radius, and therefore the pdf for the approximation noise can now be derived.

The approximation noise generated for the case L = 5, along with the marginal pdf of the radius `r' are shown in Figure 3.7. Since the marginal pdf of the radius is linear, and the approximation process uniformly divides it into L parts, the pdf contribution for the approximation noise also is staircase in nature (Fig. 3.8).

The area of the rectangles of Fig.3.8 give the intercept value for the straight line (pdf of approximation noise). Similarly the area of the triangles give the slope value. Therefore for any value of `L', we get the pdf of the approximation noise as shown in Figure 3.9, i.e with the intercept equal to "L/k" and slope equal to $-2L/k^2$.

3.3 THE NOISE PROBLEMS

3.3.1 The CSANR

The equation for the pdf of approximation noise is,

$$f_q(q) = \begin{cases} \dfrac{-2L}{k^2}\; q + \dfrac{L}{k} & ; \; -\Delta/2 \le q \le \Delta/2 \\ 0 & ; \; \text{elsewhere} \end{cases} \tag{3.18}$$

It can be verified that,

$$\int f_q(q)\, dq = \int_{-\Delta/2}^{\Delta/2} \left\{ \left(\frac{-2L}{k^2} \right).q + \frac{L}{k} \right\} dq = 1.0$$

and

$$E\left[q^2\right] = \frac{\Delta^2}{12} = \frac{k^2}{L^2.12} \tag{3.19}$$

Also we can find that,

$$E\left[r^2\right] = \int_0^k r^2 \left\{ \frac{2}{k^2} \, . \, r \right\} dr = \frac{k^2}{2} \tag{3.20}$$

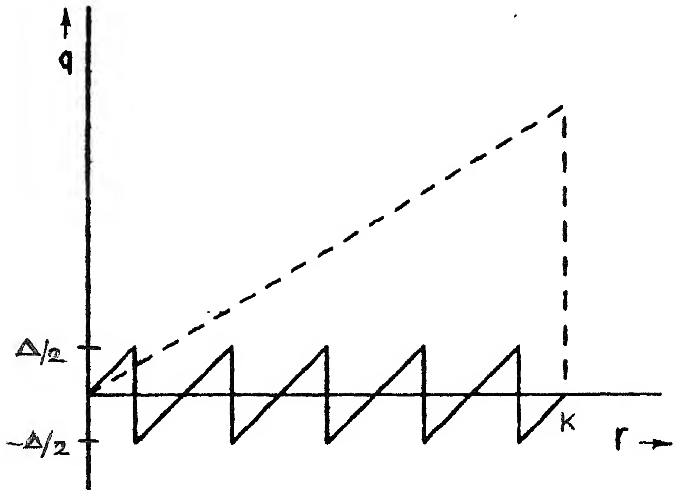


Fig.3.7 Approximation noise for L = 5

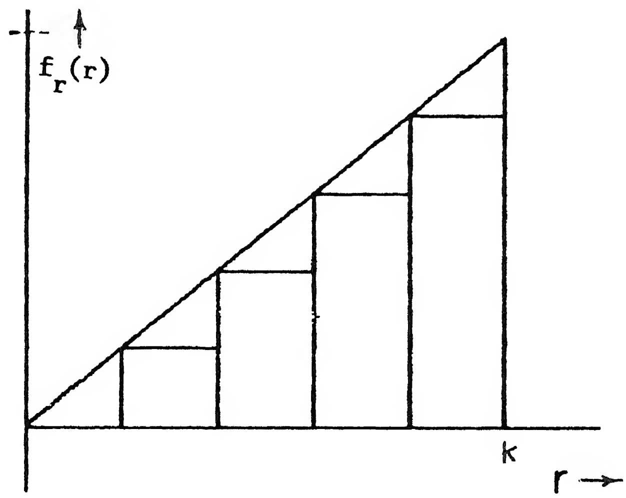


Fig.3.8 Marginal PDF for R and approximation

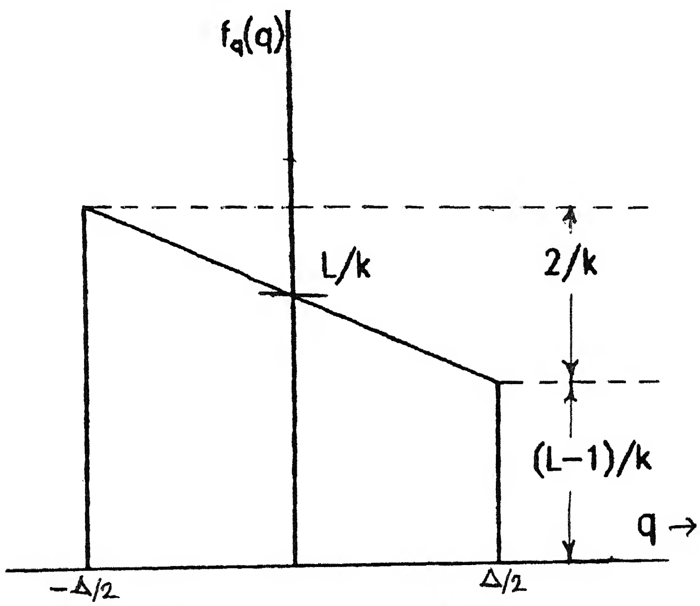


Fig.3.9 PDF for the approximation noise

Therefore,

$$\text{CSANR} = \frac{E\left[r^2\right]}{E\left[N^2\right]} \cdot \frac{1}{2\pi} \tag{3.21}$$

Recalling that, $1/2\pi$ is the pdf for θ, which must also be included for covering the entire color plane,

$$\text{CSANR} = \left\{ \frac{k^2/2}{k^2/L^2.12} \right\} \cdot \frac{1}{2\pi} = \frac{3}{\pi} L^2 \tag{3.22}$$

$$\text{CSANR (in db)} = 20\log_{10} L - 0.2 \text{ db.}$$

3.3.2 Additional SNR Burden

The dynamic range of the two original chroma signals U and V are +0.9 to −0.9, and +0.7 to −0.7 respectively. For the purposes of television transmission they are weighted by the factors 0.493 and 0.877 respectively [10]. The difference in the dynamic range, and the difference in the weighting factors of the two signals create problems while calculating the SNR. Hence to avoid confusion, conveniently we handle the normalized dynamic ranges for both the chroma signals and therefore the absolute values can be found by multiplying with an appropriate constant.

In section 3.1.3, we have obtained the normalized spiral length i.e. X value by squaring the `C' value. However for calculating the additional SNR burden, we require the actual length of the spiral. The calculations are as follows. Starting with the point on 0^o axis with radius vector r_i, one encirclement of the spiral results in the end point with a radius vector r_o and

$$\text{length of this portion of spiral is} = 2\pi\left[\frac{r_i + r_o}{2}\right] \tag{3.23}$$

$$\text{Therefore the length of the spiral is} = L.\pi \left[r_{is} + r_{os}\right] \tag{3.24}$$

where,

r_{is} : Innermost radius of the spiral

r_{os} : Outermost radius of the spiral.

Substituting, $r_{is} = 0.0$, $r_{os} = 1.0$,

$$\text{The length of the spiral} = L.\pi\left[0+1\right] = L\pi \qquad (3.25)$$

Since, we consider the normalized dynamic range of the original signals, the ratio of the spiral length and original dynamic range of U-V signal is given by

$$\frac{L\pi}{1} = L\pi$$

$$\text{The additional SNR required (in db)} = 20\log_{10}(L\pi).$$

This is the additionally required SNR, for the purposes of noise tolerance. In other words, to have the same noise effect in case of the new signal as that of the original signals, the SNR of the new signal should be $L\pi$ times more than that of the original signals (certainly a big price, in case of large L value!).

3.3.3 The Conflicting Demands on `L' Value

From the results of sections 3.2.1 and 3.2.2, we get

$$\text{CSANR (in db)} = 20\log_{10}(L) - 0.2$$

$$\text{Additional SNR (in db)} = 20\log_{10}(L\pi)$$

The list of these values for different L are shown in Table - 4.

Table 4

L	6	7	8	9	10	12	14	16
CSANR (db)	15.36	16.70	17.86	18.88	19.80	21.38	22.72	23.88
Additional SNR (db)	25.50	26.84	28.00	29.03	29.94	31.53	32.86	34.03

As is evident,

a) For better approximation, i.e. for less approximation noise, the L value must be increased.

b) At the same time, increase in L demands increase in the required "additional SNR".

Thus these two demands on L value contradict each other (like tax fixation). Apart from this, the effect of such an approximation, on color perception, is the major deciding factor in selecting the value of L.

3.4 THE L VALUE ESTIMATED FROM JND STUDIES

In this section, we try to find the requirement of L by extending the JND concept mentioned in section 1.2.3. According to [7], the JND ellipses can be obtained for any color point in chromaticity diagram. Since the spiral approximation is conveniently performed in the color plane, we try to extend the results of [7] to the color plane, to obtain the required L value.

3.4.1 JND Ellipses in Color Plane

To do this, the following steps are undertaken :

1) First of all, we choose particular reference color points in the color plane. Then we transform these points to get the chromaticity co-ordinates x, y.
2) Using [7], the interpolated data are obtained and using these data, JND ellipses are drawn in the chromaticity diagram.
3) The JND ellipse points are once again transformed back to the color plane to get the JND ellipses in the color plane.

While doing so, we assume a particular Y value to begin with the chosen color points in the color plane (UU, VV). Hence, the JND ellipses obtained are true only for the assumed Y value. Therefore, for different

values of Y (0.2, 0.4, 0.5, 0.6 and 0.8) the JND ellipses are obtained and are shown in Fig. 3.10. The respective chromaticity diagrams with JND ellipses are also shown in the figure.

3.4.2 Observations and Analysis

From the Fig. 3.10, we can observe that,

1) As Y increases, the size of JND ellipses increases.
2) For more saturated colors, the size of JND ellipses are bigger than that of less saturated colors.
3) The JND ellipses along the blue color, differ from that of other JND ellipses. However, more blue colors, exists at lower values of Y, where (at Y = 0.2 here) the JND ellipses are comparable.

However, the following factors, question the extent to which the data can be used.

1) The interpolated data obtained from [7] could be erroneous along the blue primary due to crowded curves, leading to wrong JND ellipses calculations along blue colors.
2) The JND ellipses are initially drawn in the chromaticity diagram only, where the Y values are not directly used.
3) In the X,Y,Z system, the Z primary is equivalent to blue color primary, and it suffers from the uneven projection effects in the chromaticity diagram. Therefore the JND ellipses drawn around blue color may not be true.
4) Intuitively, one may expect that the size of JND ellipses would increase as the Y value decreases., because the color perception at low illumination is hampered to a great extent. However, such effects are not seen in the JND ellipses obtained for different Y values, and the reasons could be the points mentioned above.

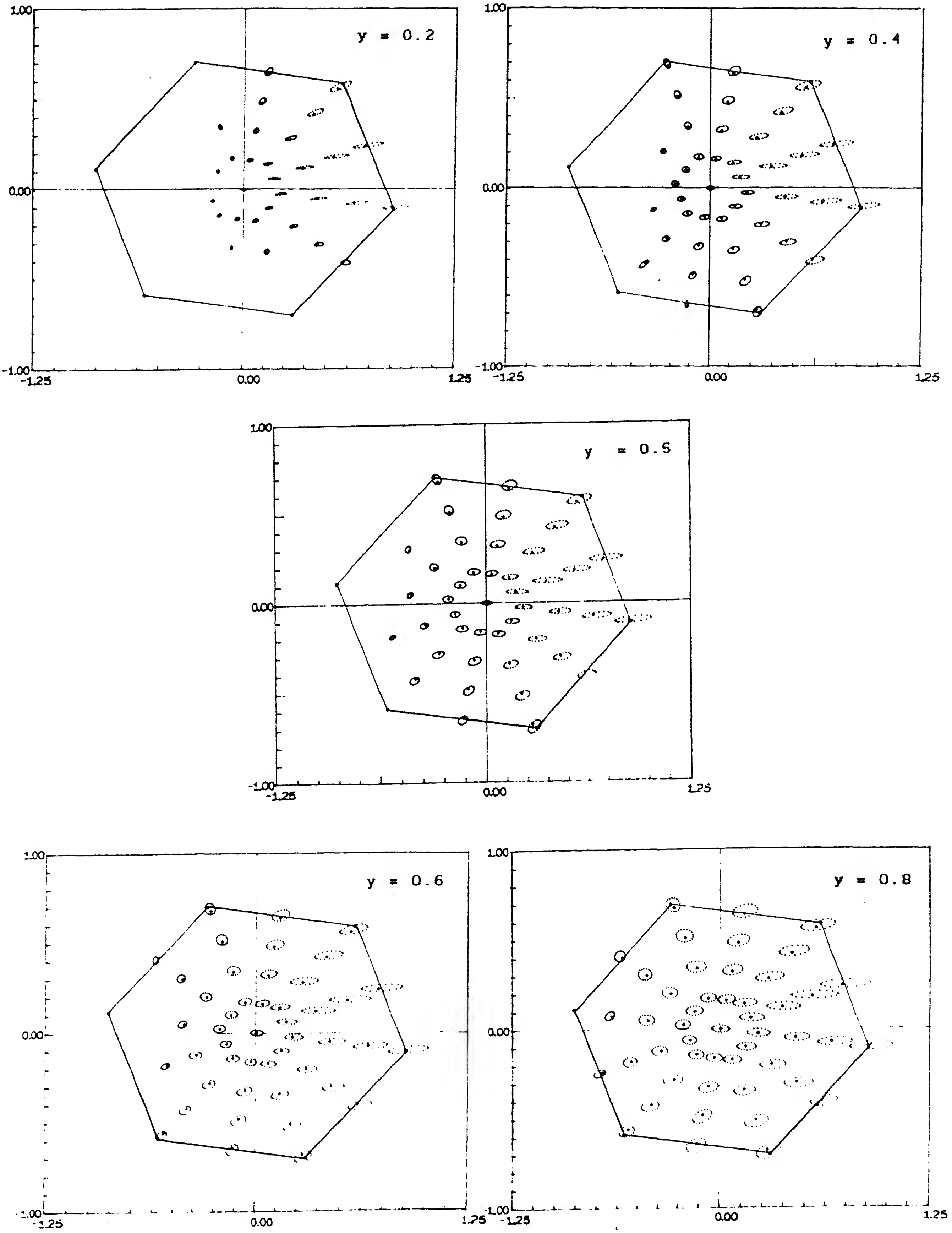


Fig 3.10 (a) JND ellipses on color plane for Y = 0.2, 0.4, 0.5, 0.6 and 0.8
(Ellipses shown enlarged by 4 times)

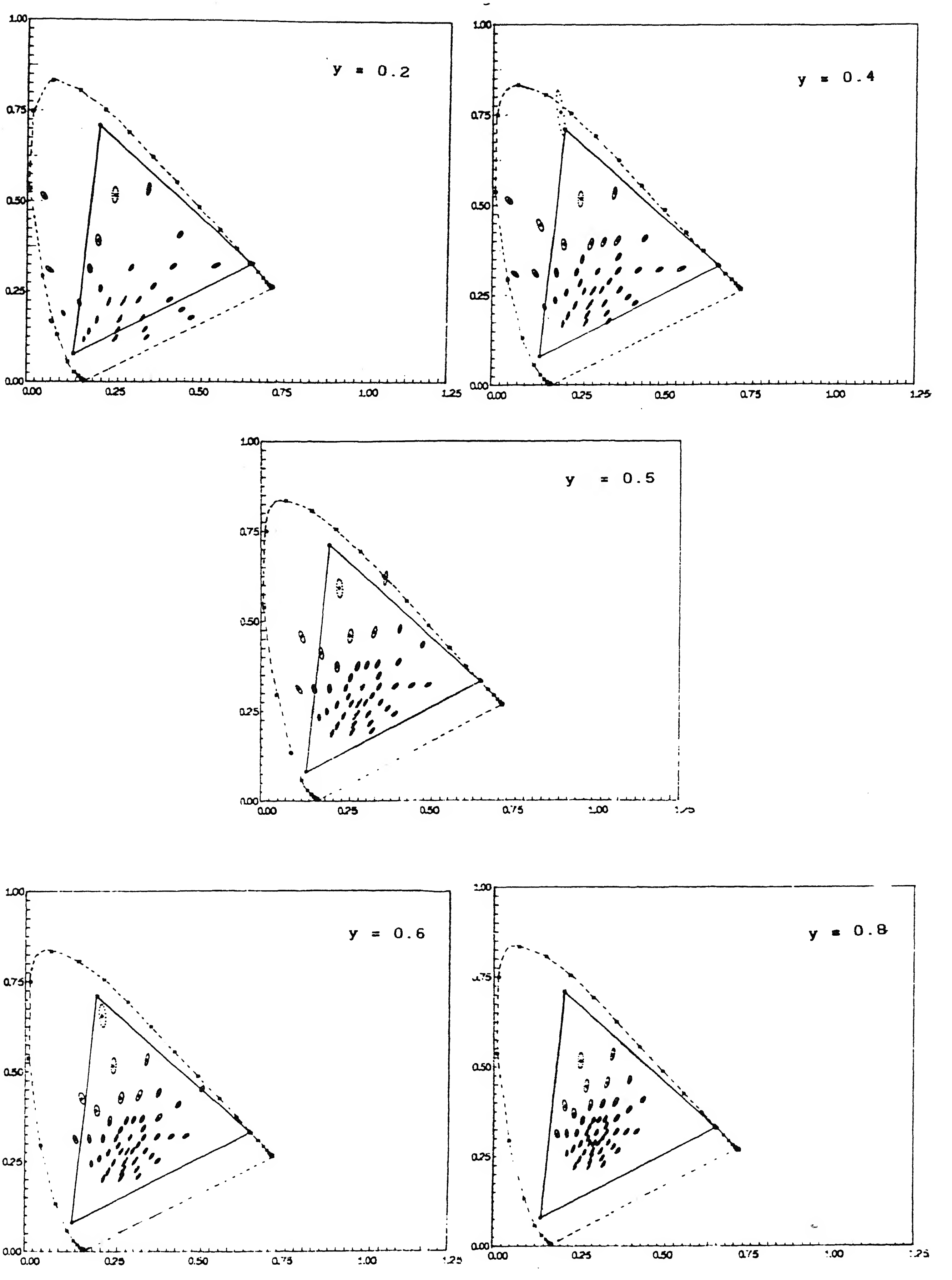


Fig 3.10 (b) JND ellipses on chromaticity diagram for Y=0.2, 0.4, 0.5, 0.6 and 0.
(Ellipses shown enlarged by 4 times)

3.4.3 Approximate `L' Value

Disregarding some of the contradictory observations in the previous section and taking the results of Y = 0.5, we can approximate the required `L' value. For this purpose, first of all the "average ellipse diameter" along the saturation vector is obtained for each phase angle. Then the "average" for all the "average ellipse diameters" obtained for all the phase angles, is calculated. This final diameter is taken as the spacing to be maintained between the two adjacent circles of the spiral. According to this procedure, the approximate requirement of L value is around 40.

3.5 EFFECTS OF NOISE

In section 3.1.3, the effect of noise was studied and the squaring was performed only for distributing the noise effect equally in the entire plane. However, this alone is not sufficient to meet the actual problems due to noise. As mentioned in 3.2.2, the additional SNR required is $20\log_{10}(L\Pi)$ decibels, and particularly when L value is large, the new signal becomes very sensitive to noise and may become unusable. The serious effects of noise and the possible solution to the problem are dealt below.

3.5.1 Deleterious Effect of Noise

For the specific case of L=5, let us assume that we have the color point shown by P_1 in Fig. 3.11, which lies just at the completion of the first spiral. The new signal value i.e. value of `C' for this point is equal to 0.2. We also get $X = C^2 = 0.04$.

Now let us assume that there is an additive noise of 5% (0.05) added with the transmitted signal X = 0.04, resulting in the erroneous color point P_2 of Fig. 3.11, which equals 0.04+0.05 equal to 0.09.
From the figure, we can observe that P_2 is exactly 180^o out of phase to P_1 i.e. P_1 and P_2 are complementary colors. For the case of L=10, with P_1 same as

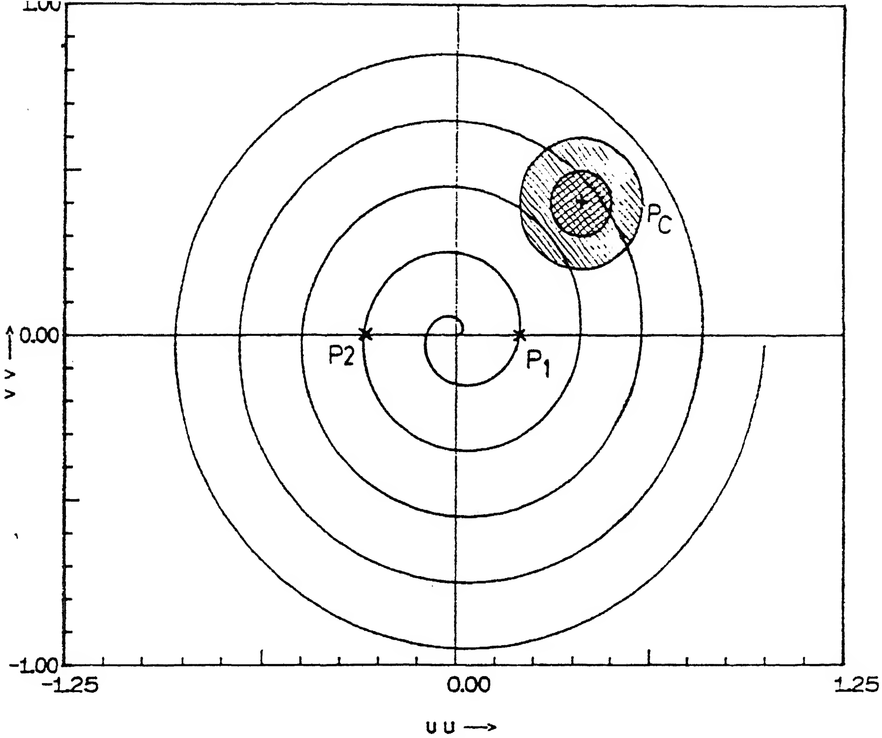


Fig.3.11 Desired effect of noise

0.04, small error of just 2.25% (0.0225) can move the point P_1 to another point similar to P_2. Such effects will result in serious color distortion and will give rise to unusable picture quality.

3.5.2 Tolerable Noise Propagation in Color Plane

Recalling the observations made in sections 2.1.1 and 2.1.2 (properties along radius and phase angle), let us consider a point in the color plane. Now due to noise, when the point changes along the saturation vector the noise tolerance is considerably more than, when the change takes place along the phase angle. As shown in Fig. 3.11, considering the color point shown by P_c, for a 5% noise the tolerable signal change is shown by the area enclosed by the inner circle with P_c as the cent re point. When the noise increases to 10%, the area over which the noise propagates also increases, about the point P_c as shown in figure.

For all the points in the color plane/spiral, such noise propagation will be more preferable because the noisy signal will be always around the

neighborhood of the actual signal. However, obviously it is impossible to have such a mapping which can render such noise propagation for all the points.

3.5.3 Scrambler for Noise Tolerance

For noise tolerance, instead of caring for each point in the color plane, the color plane can be considered as made up of many small similar areas arranged systematically. In such an arrangement, the noise would change the point within the small area only (when the percentage noise considered is lesser than the percentage of small area over total area). For this purpose, we should find the number of small areas.

3.5.4 Scrambler Design

The standard quality grading for the reproduced pictures, used for television transmission says that the SNR of 28 db (25 times) gives "marginal" quality, SNR of 22 db (12 times) gives "poor" quality, and SNR below 22 db becomes "unusable".

For our calculations, we take 26 db (20 times), as usable quality i.e. a maximum of 5% noise. Therefore, we have to split the color plane into 20 small areas. The areas split should nearly resemble a circle so that the effect of noise would be minimal (as stated earlier). Refer to Fig. 3.12, the area of the circle with radius equal to 0.5, encloses 1/4th of the total area (with radius equal to 1) of the color plane. Therefore the ratio of the number of small areas, within half radius and within full radius should be 1:4 implying 5 small areas within the half radius circle as shown in Fig. 3.12, for a total of 20 small areas.

We assume that the spiral approximation is already performed and we are dealing only with the spiral points in the color plane. For ease of explanation, we also assume that L=6. Therefore, 3 circles of the spiral will be covered by the half radius area i.e. the small areas from a_i to e_i, with

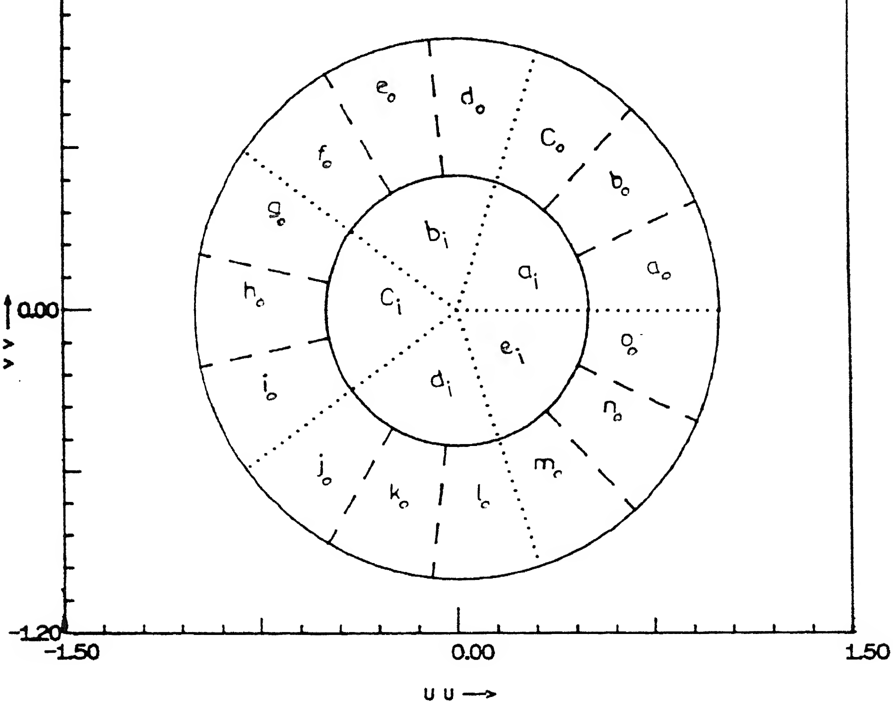


Fig.3.12 The area splitting for scrambler

reference to Fig. 3.12. The rest of the 3 outer circles of the spiral will be covered by the small areas from a_o to O_o.

To begin with, let us consider the half radius area. In Fig. 3.13, the small piece of the first circle in the area a_i is known as $1a_i$, where the 1 stands for the first spiral. The area a_i also has pieces of second and third circles denoted by $2a_i$ and $3a_i$. Similarly, the other areas also have pieces of spiral. The same is true for the outer areas a_o to O_o. But they have the pieces ($4a_o$, $5a_o$, $6a_o$), ($4b_o$, $5b_o$, $6b_o$) and so on, for the areas a_o, b_o etc. respectively.

As assumed, using the approximated, squared signal value we define a new signal X_s referred to as the scrambled X signal. The value of X_s for a given value of X is obtained as follows :

Referring to Fig.3.13, we start at the origin with the value of X_s=0.0. As long as the X signal lies in $1a_i$ i.e. from origin to point P_1, the X_s signal has the same values as that of the X signal. After point P_1, for any further increase in signal values, the X signal will increase along $1b_i$, whereas the X_s signal will jump from point P_1 to point P_2 in $2a_i$ and will

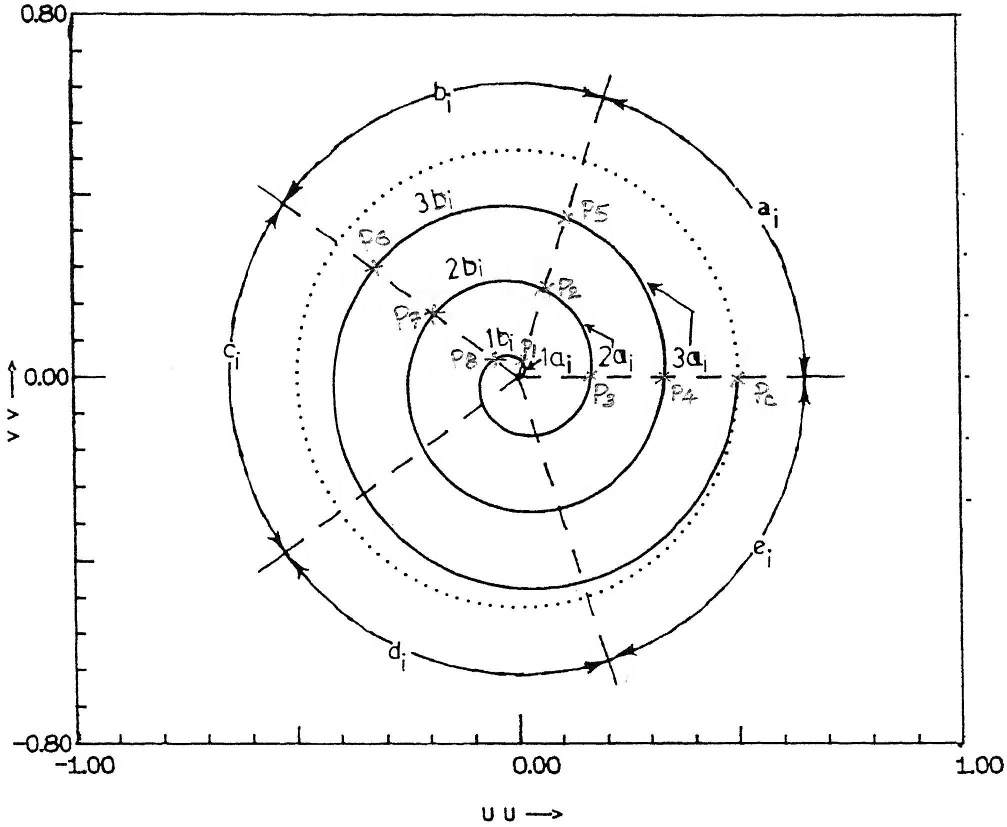


Fig.3.13 Half radius area of the color plane (with spiral L = 6) shown enlarged with identifications for chosen pieces of spiral

increase along $2a_i$ in the reverse direction, until it reaches point P_3. After P_3, once again the X_s signal jumps to point P_4, and any further increase in the signal value will be along $3a_i$, until it reaches the point P_5. In this way we cover the entire area a_i. Further increase in signal X_s will start covering the area b_i i.e. from point P_5. The X_s signal increases along $3b_i$, $-2b_i$, $1b_i$ (- for reverse direction, with jumps at points (P_6, P_7) and (P_2, P_1) and reaches the point P_8 covering the area b_i.

Similarly, the rest of the small areas c_i, d_i and e_i are also covered and the X_s signal reaches point P_c, thus covering the half radius area of the spiral. Now, similar to the signal paths of small areas a_i to e_i, the signal along the small areas a_o to O_o are also covered; but here the number of small areas are 15 instead of 5. This alphabet scrambling is shown in Fig. 3.14, for the first three circles of the spiral, when L=6.

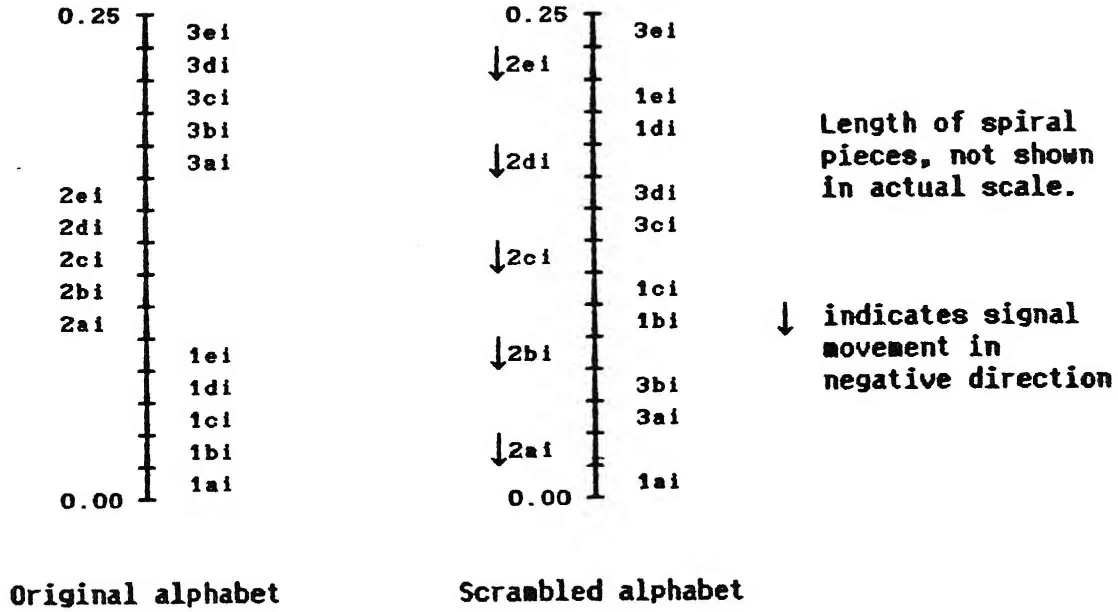


Fig.3.14 Alphabet scrambler

3.5.5 Design Justifications

A natural question arises here is that if we require the signal path as given by the scrambled alphabet structure given so far, why can't we approximate the color plane directly as required, instead of performing the spiral mapping, squaring and then scrambling the alphabet?

The answers are

1) The structure of spiral mapping, and the properties of chrominance signals used to make the approximations in the color plane are well established. Hence, it is preferable to do a spiral approximation such that the scrambling can be done easily.

2) In case, when good results are not obtained due to scrambler, we can attempt some other techniques and therefore it is preferable to start with the spiral approximation.

3) Primarily, the aim is to find a suitable means for combining the two original chroma signals into single signal without compromising too much on the fidelity and not on an efficient realization of the system.

5.5.6 Effects of Scrambler

The alphabet scrambler designed above, meets our requirements of splitting the color plane into 20 small areas and grouping them systematically for tolerable noise propagation. Therefore, the effect is that when the noise is within 5%, the reproduced picture quality is expected to be tolerable. Also such scrambling will not alter the bandwidth requirements. The L value chosen for the experiment is `6'. For any suitable L value such alphabet scrambling can be performed. Also operations performed by scrambler is linear,i.e. assembling the pieces of the alphabet differently. Therefore, it is expected that, the bandwidth of the scrambled signal will not be different from that of the original signal.

CHAPTER - 4

EXPERIMENTS AND RESULTS

The experiments and results mentioned together in this chapter, as they became inseparable in the manner the experiments were conducted. This interactive approach was followed throughout experiments.

4.1 THE EXPERIMENT RELATED ISSUES

There were many aspects to be considered before beginning the experiments and they are discussed below.

4.1.1 The Hierarchy of Experiments

Experimentation begins with the spiral approximation in the color plane. Because such an approximation has a bearing on the perception of colors to judge its validity. Next the value of `L' actually needed must be found. Further, the experiments on bandwidth limitation, the effect of noise on the new signal, and the use of alphabet scramblers designed for noise problems, needed to be carried out.

4.1.2 The Experimental Set up

The experiments are simulated on the HP-TSRX computer systems. The source code is written in C language and for the graphics purposes, "STARBASE" routines are used. The data handled for experiments were 8 bits in depth for each primary color and the monitors used during experiments had the full 24 bits depth (3 colors x 8 bits each) color reproduction.

4.1.3 The Test Images

Since the work is fundamentally on "COLOR REPRODUCTION" the test images should contain the entire spectrum of colors. Therefore, the standard test images like LENNA and others are not used and two test images of size [512]x[512] containing many different colors, were scanned for conducting the experiments. For identification, they are named as FIRST-IMG (Image with fruits) and ASHISH-IMG (Image with close-up of Lord Krishna). The standard "BABOON" test image is also used for experiments wherever needed.

4.1.4 The Filters Used

For bandwidth limitation analysis, mainly three IIR filters were designed for 1.3 MHz, 3.3 MHz and 4.3 MHz (2.2 MHz filter was already available with DSP routines mentioned in section 4.1.5). The filters were designed using the package "FILTER DESIGN and ANALYSIS SYSTEM (FDAS)", version 2.1, developed by Signal Processing Division, NPOL, Cochin. All the filters designed are based on Bilinear transformation and 16 bits are used for quantising the filter coefficients. The filter structure for the designs are "CASCADED SECOND ORDER SECTION FOR FLOATING POINT IMPLEMENTATION". The filter coefficients and other details are given in Appendix-B.

4.1.5 Implementation of DSP Routines

The DSP routines like IIR filter implementation, FFT of signal sequence and noise test simulations etc. are obtained from the programs given in the book "C LANGUAGE ALGORITHMS FOR DIGITAL SIGNAL PROCESSING" [11].

4.1.6 The Photoplates for Output

For evaluating the results of experiments, the photographs are taken for all the experiments. The necessary specifications are also shown in the

photoplates. Since the color gamut of photography is wider than the color gamut of monitors, no color distortion can be expected in the photoplates. However, the reference white need not be same for photographs and monitor, and hence the corresponding small color shift can occur in the full photograph. To compensate for such distortions, while taking the photographs, the original images are also taken together with the processed images. Hence the color distortions will be the same for both original and processed images, and therefore the processed image can be compared with original image without any compromise.

4.2 THE SPIRAL MAPPING AND RESULTS

4.2.1 The Processing Steps

The data for any pixel in R,G,B are transformed to Y, UU, VV. The Y is preserved and with a particular L value, the UU and VV are approximated to get `C' value. Now, for any pixel we have only two quantities Y and C, instead of R,G,B or Y, UU, VV. Refer Fig. 4.1.

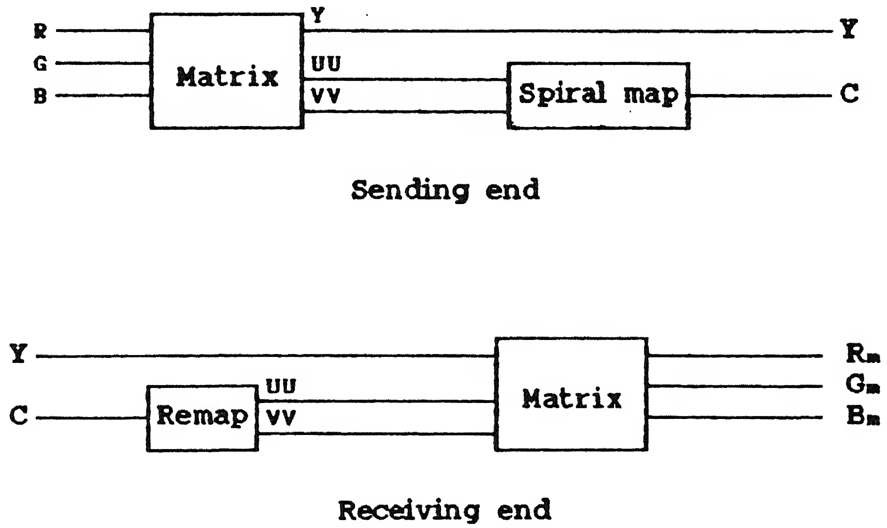


Fig.4.1 Simple spiral approximation - Processing steps

To get back the image from these two quantities, we do the inverse operations. Using `C' we obtain the approximated UU_m and VV_m quantities using the formulae,

$$UU_m = C.\cos(2\Pi LC) \tag{4.1}$$

and

$$VV_m = C.\sin(2\Pi LC). \tag{4.2}$$

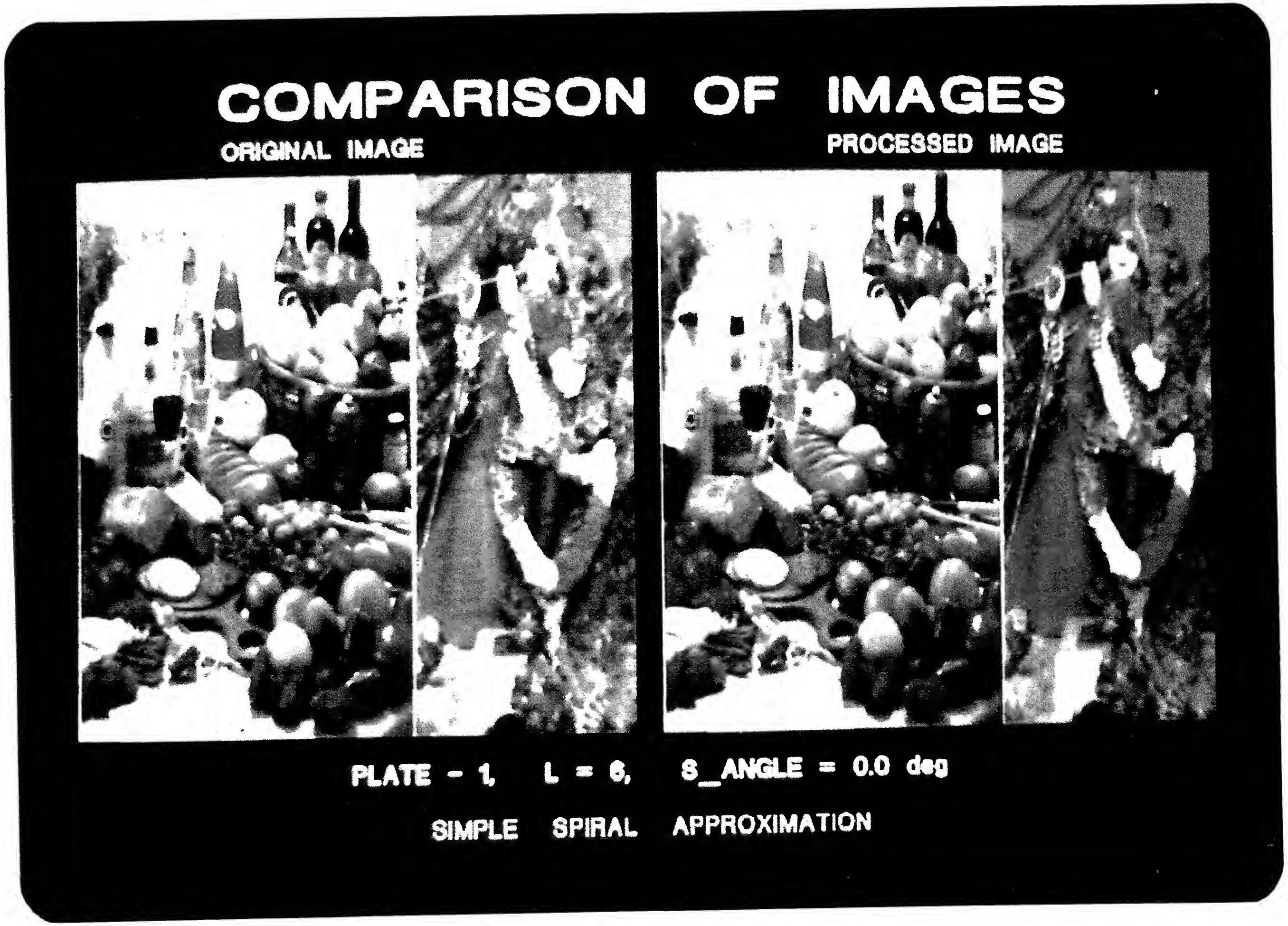
The Y, UU_m, VV_m data are transformed back to R, G, B. This process is repeated for all the 512x512 pixels of the image, and both the original and processed images are displayed.

4.2.2 The Experimental `L' Value

To our surprise, just for the L values around six (6), the processed image had all the different ranges of color, compared to that of the original image [Plate-1]. Only with an apriori knowledge that the two images in plate-1 are different, the very small differences can be found, otherwise they look indistinguishable. The result is same for all the three test images (ASHISH-IMG, FIRST-IMG and BABOON-IMG).

4.2.3 The Actual Bandwidth of `C' Signal

For bandwidth analysis of the new signal `C', the bandwidth of the original signals UU and VV are band limited to 1.3 MHz (the standard used for PAL television) using filter 1 given in Appendix-B, before doing the spiral approximation. Contrary to the results of derivations in section 3.1.4 for an L value of 6, the signal C occupies the entire 5 MHz range. Even for larger values of L ($\geq$ 40), the spectral power at high frequencies reduces but not significantly (around 15 db less). The reason for more spectral energy for lower L (= 6) values could be the quantization noise as already mentioned in section 3.1.4.


COMPARISON OF IMAGES
ORIGINAL IMAGE
PROCESSED IMAGE
PLATE - 1, L = 6, S_ANGLE = 0.0 deg
SIMPLE SPIRAL APPROXIMATION

4.2.4 Effects of Filtering

When the `C' signal (obtained as given in section 4.2.3) is filtered by the same filter used for UU and VV signals, the processed image could not be discerned at all, and almost the full image is lost. This is true for all the three test images. Also for any choice of L, the effects are same on all the images. The reason for such debacle was found and is given below. Like noise, the action of filtering also alters the signal values. Particularly whenever edges occur (high frequency) in the image, sharp transitions are smoothened by the filter. While doing so, effectively the signal values are altered very much and hence false colors (when the color point moves along the spiral) are reproduced due to the smooth transition. Therefore, the alphabet scrambler developed for noise reduction must be used before filtering the new signal. By doing so, the altered color points due to filters will be around the neighborhood of the original point.

To do this, from the C signal, we should get X signal (by squaring C, for the reasons given in section 3.1.3) and then using the scrambler,obtain the scrambled signal X_s. This X_s signal is then filtered. The filtered X_s signal is descrambled at the receiver to get X from it, and the square root of the X signal is taken to get C signal. Using Y and C signals, the processed image data is obtained in R, G, B as mentioned earlier. Refer Fig. 4.2. Though there were improvements due to scrambling, it was not adequate to get atleast a "Marginal" quality picture.

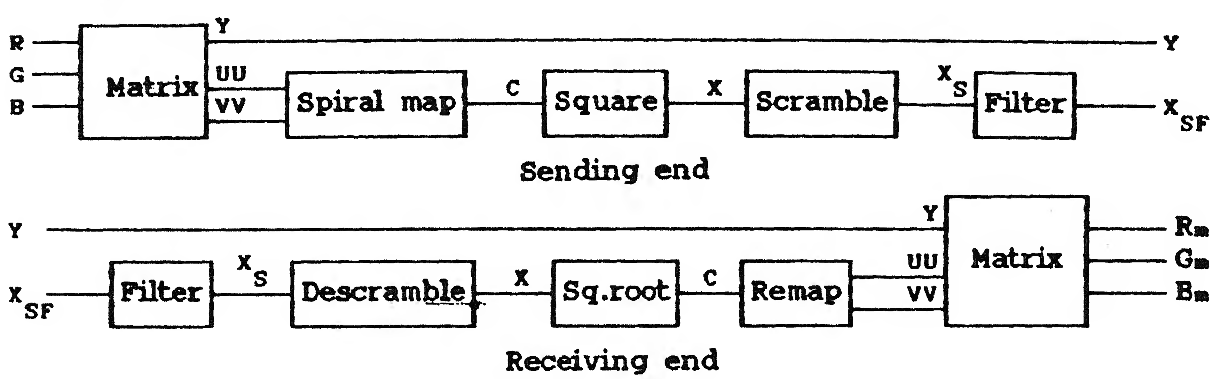


Fig 4.2 Block diagram for simple spiral, squared and scrambled. (To reduce filtering effects)

4.3 Modifications on the Spiral

The reasons for such serious effects of filtering were analysed in depth, and modifications needed in spiral approximation as discussed below.

4.3.1 Observations

As already mentioned in section 2.2, the actual color gamut is varying as Y varies. For chosen Y values (0.1, 0.5 and 0.9) the full color gamut and the varying color gamut are once again shown in Fig. 4.3, along with the spiral.

As can be seen in the figure, for both the low and high values of Y most of the spiral lie outside the actual color gamut. Even for Y = 0.5, where the actual color gamut is the biggest, it does not cover the full spiral.

This clearly indicates that the full range of the new signal is not efficiently utilized and therefore leads to lesser signal power available for the new signal.

Also, the squaring operation to obtain X signal reduces further the signal power, since the dynamic range of C signal is from 0.0 to 1.0 only. Hence the net effect is that, when this very low power signal is filtered, the percentage change in signal value compared to the full range of signal alphabet is very high and hence serious distortion takes place.

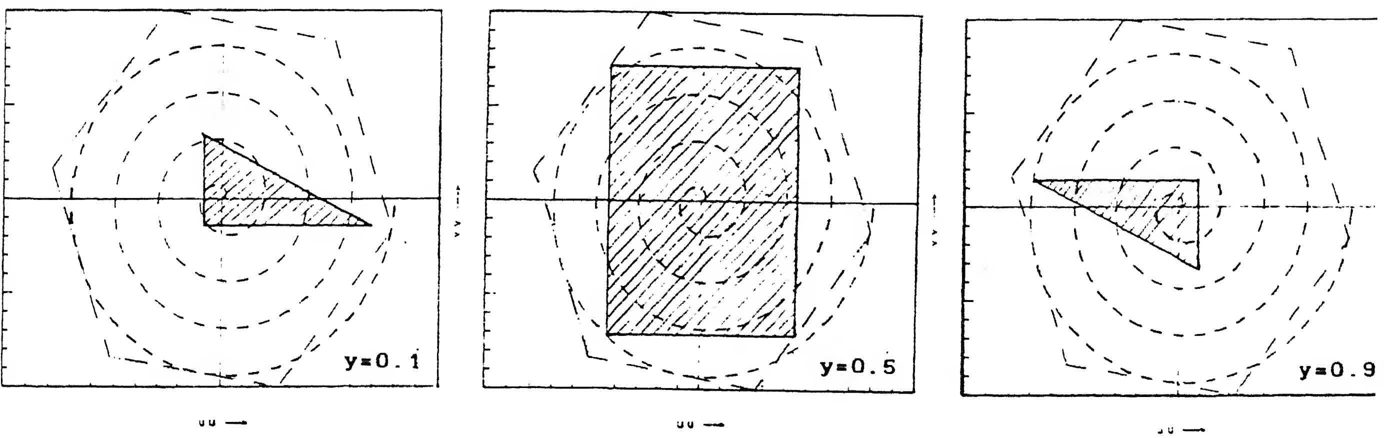


Fig 4.3 Varying color gamuts with simple spiral

4.3.2 The Required Varying Spiral

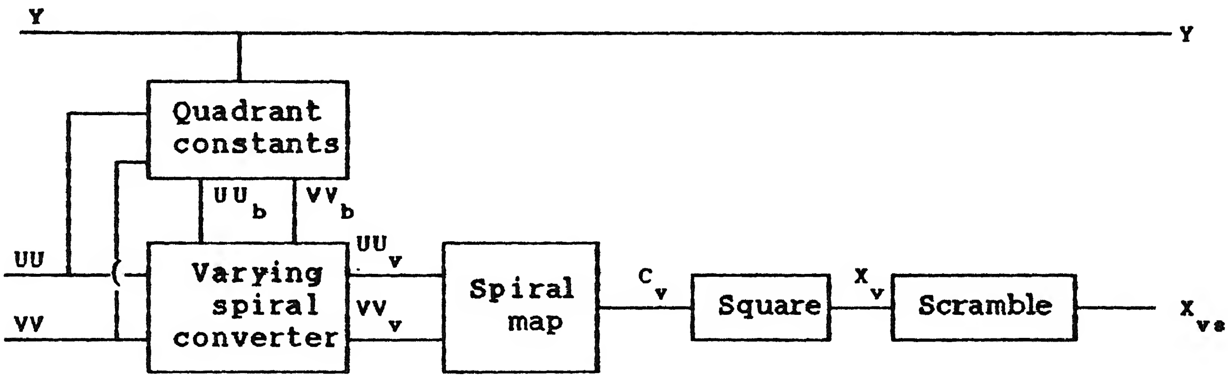
To get the maximum signal power, the total alphabet range must be used. Therefore essentially the spiral should lie within the varying color gamut through out the range of Y values. At the same time, all color points in the varying color gamut must also be covered by the spiral. Hence the spiral size and shape should vary as Y varies. Obviously, due to the curved nature of spiral, the points near the sharp corners of the varying color gamut cannot be covered. However these outer color points are mapped on to the outermost circle of the spiral in the respective phase angles. Though such an attempt approximates the outer colors to a large extent, the idea is not to ignore these colors.

Very importantly, the starting point of the spiral must not be changed from the origin of the color plane, because the mapping is always done by preserving the phase angles with respect to the origin. If the starting point of the spiral is moved to some point other than the origin, then with respect to the new starting point only the mapping can be done and therefore the originality of the phase angle will be lost.

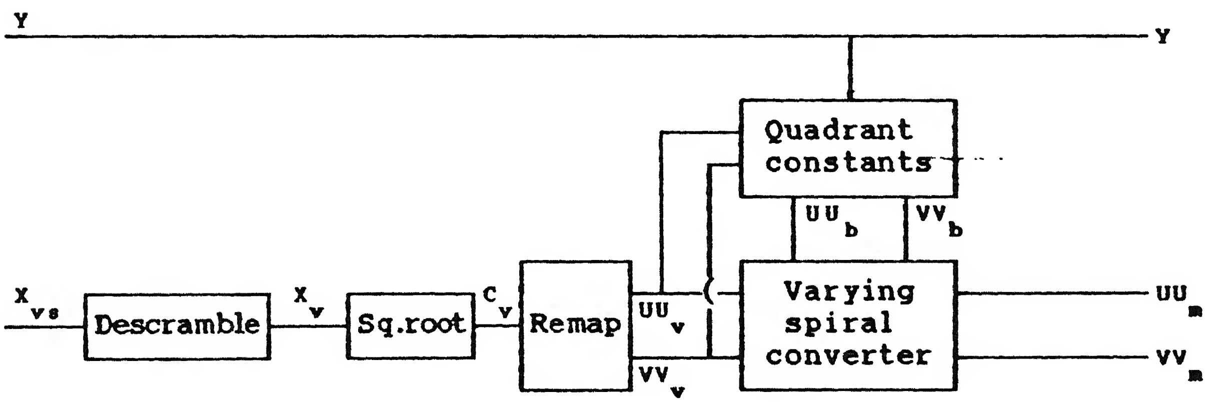
4.3.3 Varying the Spiral

The color point under consideration with a particular radius and phase angle will lie in the varying gamut. The phase angle value will have to be preserved and the radius only has to be altered according to the varying gamut. For any particular Y value, the varying gamut will be different and unique. If the size and shape of the "varying color gamut" can be altered nearly to a unit circle, for all values of Y, then the simple (unity) spiral mapping can be performed as was done earlier. Obviously, it is neither preferable nor possible to vary the entire structure of the spiral through out the Y values. Instead it is easy to alter each color point values suitably.

For this purpose, four suitable constants each for 1) positive UU axis, 2) negative UU axis, 3) positive VV axis and 4) negative VV axis will be found, in such a way that when these constants are multiplied in the respective axes, the scaled varying gamut will have unit radius in all these four directions. With these constants, a suitable constant along any phase angle can be calculated as below. First of all, the quadrant in which the phase angle lies is found and the two constants of the quadrant are picked from the four constants.



Sending end



Receiving end

Fig.4.4 Block diagram for varying spiral approximation

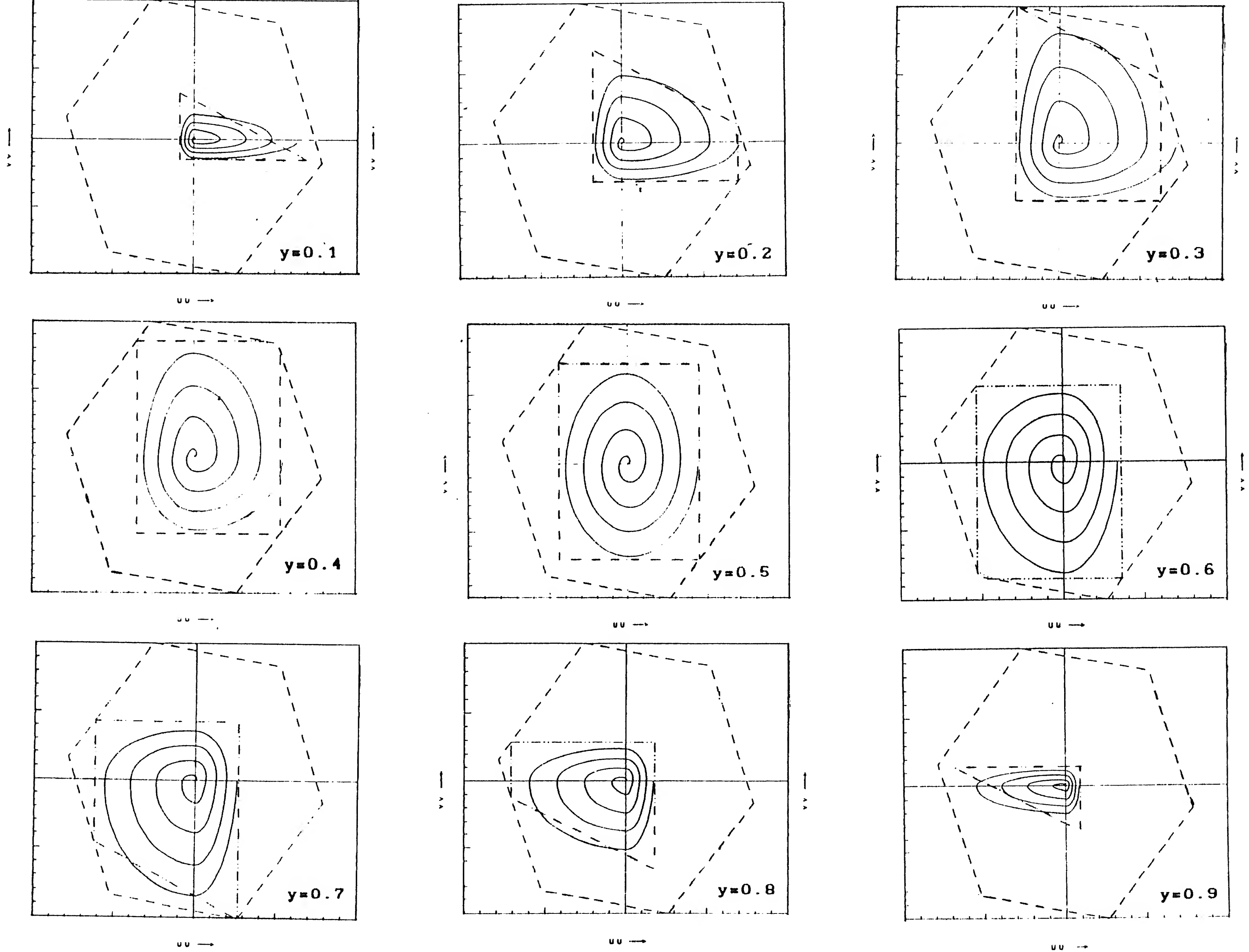


Fig 4.5 Varying spiral for different Y values

An example, to get these two constants, for a given Y, UU and VV values, is given in next section. Using these two constants and the phase angle, the constant (C_n) along the phase angle of our interest can be calculated as,

$$C_n = \sqrt{\left[\frac{\cos(\text{angle})}{UU_b} \right]^2 + \left[\frac{\sin(\text{angle})}{UU_b} \right]^2} \qquad (4.3)$$

where

UU_b : constant along UU axis (positive or negative)

VV_b : constant along VV axis (positive or negative)

angle : original phase angle.

The radius of the color point will be scaled by this constant "C_n".

This new radius value, and the original phase angle are the equivalent quantities of the varying (unity) spiral within the varying color gamut. Using this radius and phase angle, we can find the `C' signal as previously.

As shown in Fig. 4.4, at the receiving end also the constant (C_n) is again calculated to get back the original radius and the remaining processings are same. The color gamuts with varying spiral for different values of "Y" are shown in Fig. 4.5.

4.3.4 The Scaling Constants of Varying Gamut

To find the two scaling constants for any Y value, the full range of Y (from 0.0 to 1.0) is considered as seven color blocks stacked one upon the other. These blocks are

1. Black - Blue Block (Y=0.0 to Y=0.114)
2. Blue - Red Block (Y=0.114 to Y=0.299)
3. Red - Magenta Block (Y=0.299 to Y=0.413)
4. Magenta - Green Block (Y=0.413 to Y=0.587)
5. Green - CyanBlock (Y=0.587 to Y=0.701)

6. Cyan - Yellow Block (Y=0.710 to Y=0.886)

7. Yellow - White Block (Y=0.886 to Y=1.0)

Between the two adjacent blocks, i.e. at the interface (Y=0.114 - Blue, Y=0.299 - Red and so on), the four scaling constants are fixed according to the varying nature of the color gamut. These values are listed in Table-5.

TABLE - 5

Y	Color	UU		VV	
		Positive	Negative	Positive	Negative
0.114	Blue	0.90 (UU_{BP})	-0.13 (UU_{Bn})	0.25 (VV_{BP})	-0.16 (VV_{Bn})
0.299	Red	0.90 (UU_{rp})	-0.35 (UU_{rn})	0.99 (VV_{rp})	-0.42 (VV_{rn})
0.413	Magenta	0.66 (UU_{mp})	-0.46 (UU_{mn})	0.93 (VV_{mp})	-0.60 (VV_{mn})
0.587	Green	0.43 (UU_{gp})	-0.69 (UU_{gn})	0.65 (VV_{gp})	-0.86 (VV_{gn})
0.701	Cyan	0.32 (UU_{cp})	-0.80 (UU_{cn})	0.44 (VV_{cp})	-0.90 (VV_{cn})
0.886	Yellow	0.12 (UU_{yp})	-0.90 (UU_{yn})	0.16 (VV_{yp})	-0.25 (VV_{yn})

Within each block, the constants' change in their values uniformly. They are obtained by finding the percentage change in their values from minimum Y value to the maximum Y value of the particular block.

For example, let Y=0.5, UU=0.5, VV=-0.1. For this Y value, the color block is magenta-green (Y=0.413 to Y=0.587). Therefore, the percentage of Y within this block (Cy) is equal to,

$$Cy = \frac{Y - 0.413}{0.587-0.413} = 0.5 \text{ (or) } 50\%$$

The constants are

$$UU_p = UU_{mp} + (Cy.(UU_{gp}-UU_{mp})) = 0.66+(0.5.(0.43-0.66)) = 0.545$$

$$UU_n = UU_{mn}+(Cy.(UU_{gn}-UU_{mn})) = -0.46+(0.5.(-0.69- -0.66) = -0.575$$

$$VV_p = VV_{mp} + (Cy.(VV_{gp}-VV_{mp})) = 0.36+(0.5.(0.65-0.93)) = 0.79$$

$$VV_n = VV_{mn}+(Cy.(VV_{gn}-VV6_{mn})) = -0.60+(0.5.(-0.86- -0.60) = -0.73$$

The two constants chosen out of these four constants are,

$$UU_b = UU_p = 0.545 \text{ (since } UU > 0.0)$$

and $$VV_b = VV_n = -0.73 \text{ (since } VV < 0.0).$$

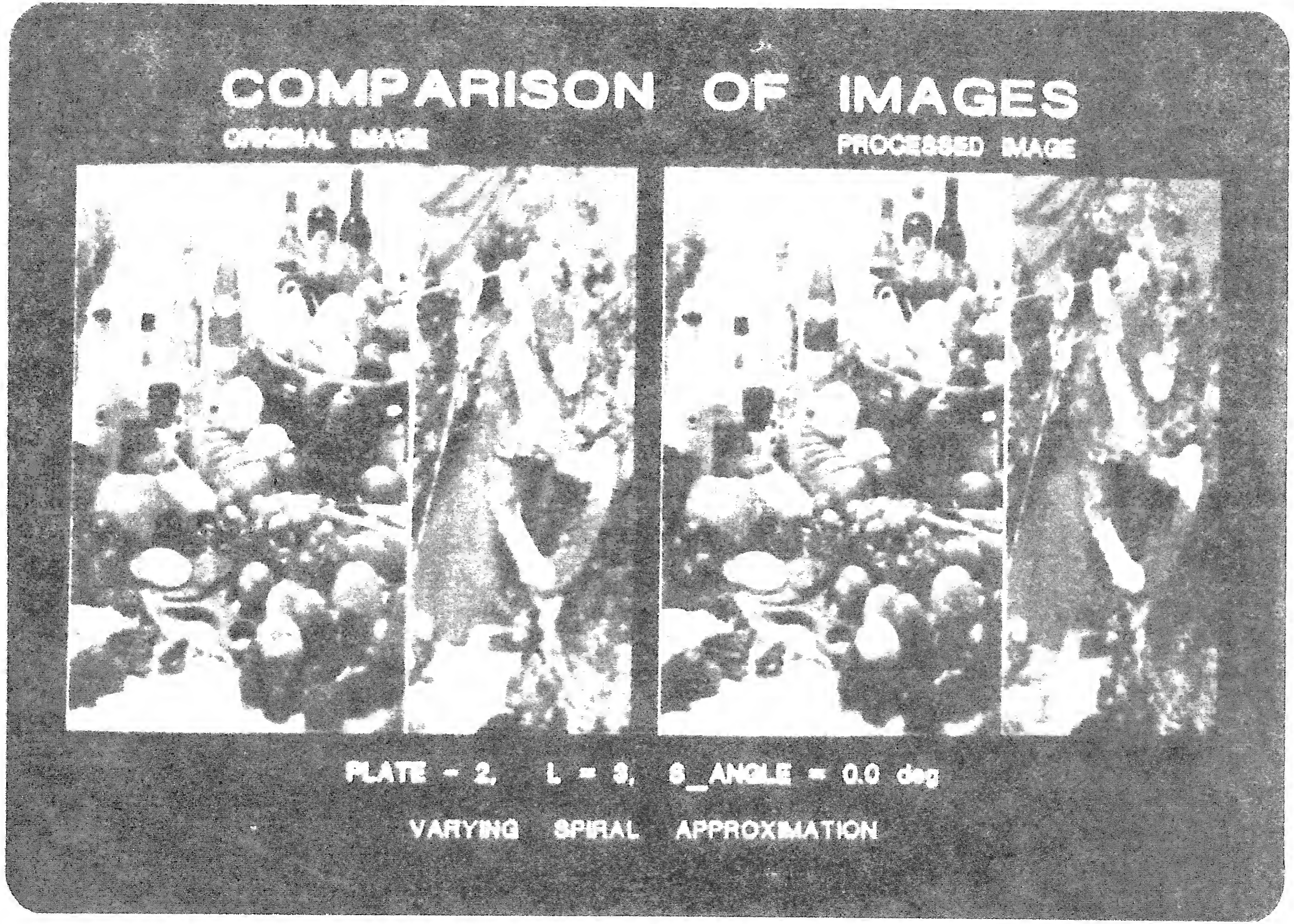
4.3.5 The `L' Value

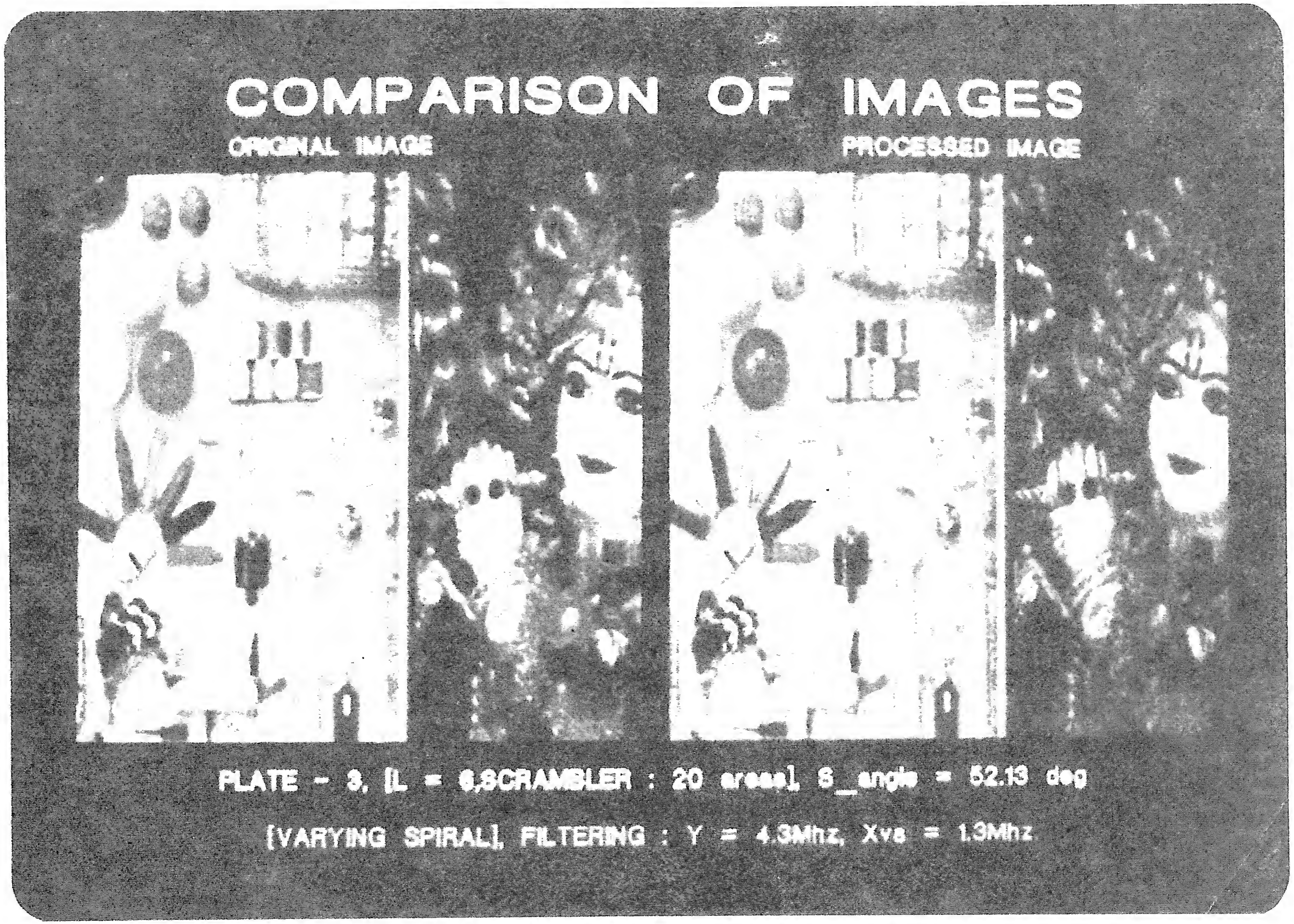
The beautiful effect of varying spiral, in comparison with the simple spiral can be well explained with any pure color, whose intensity varies from 0.0 to the maximum (in case of red color it will be from 0.0 to 0.299).

Due to simple spiral approximation, depending upon the L value, only "L" shades of red color will be obtained (similar to quantization of any signal) at the processed output. Where as due to varying spiral approximation, irrespective of the L value, a range of smooth, continuous red shades will be obtained after processing. This is true for all spectral colors. Although the maximum color purity cannot be obtained (due to the uncovered sharp corners of varying gamut), even with a very low value of L, as small as 3, infinite shades of any single color are available. As a result with L value of just "3", a very reasonable picture is obtained [Plate-2]. Due to coarse approximation (because of very low L value), in few objects, color changes can be perceived when observed closely.

4.3.6 The Filtering of Varying Spiral Signal

With the varying spiral also, the alphabet scrambler was very much essential to have reasonable results and therefore the squaring operation is performed before scrambling. However, it is agreeable that (unlike the simple spiral) with varying spiral we need not strictly have the squaring operation. However, without squaring (with a suitable scrambling) the processed images had color desaturation effects noticeably. Therefore squaring is performed for


COMPARISON OF IMAGES
ORIGINAL IMAGE
PROCESSED IMAGE
PLATE - 2, L = 3, S_ANGLE = 0.0 deg
VARYING SPIRAL APPROXIMATION


COMPARISON OF IMAGES
ORIGINAL IMAGE
PROCESSED IMAGE
PLATE - 3, [L = 6,SCRAMBLER : 20 areas], S_angle = 52.13 deg
[VARYING SPIRAL], FILTERING : Y = 4.3Mhz, Xvs = 1.3Mhz

all the experiments with varying spiral. But some other non-linear operations like logarithmic operation may be used instead of squaring.

The effect of filtering the varying spiral signal (after squaring and scrambling) showed very good improvement. Full range of colors, and very intelligible picture was obtained as a result. But with many magenta color points sprayed all over the picture, an overall slight magenta color shade was observed. The photo plate-3 shows this effect for ASHISH-IMG (along all the three test images, this image is more sensitive). The bandwidth of the varying spiral signal also occupied the entire band of the spectrum (5 MHz) for all the test images.

4.3.7 Spiral Angle

For all the experiments conducted so far, the spiral starting/ending for both simple and varying spiral were at 0°. However, change in this spiral angle (S-angle) had a wide effect all over the range from 0° to 360°. For the scrambler used until now, the S-angle at which the best results obtained is 52.125° i.e. along magenta color! The Plate-3 image is processed with this S-angle only.

The reason for the S-angle effect can be explained as given here. Although the phase angle is preserved, the radius of the varying spiral is changed. Therefore, squaring `C' signal to get X signal, for the interpretation of normalized spiral length is not valid fully as in the case of simple spiral. Though the overall length of each encirclement of the varying spiral obeys the squaring law for alphabet distribution, the varying length in the four quadrants does not obey this relation, thus leading to slight uneven noise distribution, along the different quadrants (wherever the length is more, the noise will have more effect).

4.4 OTHER EXPERIMENTS

With the varying spiral, experiments were conducted to design better scrambler and a reasonable design was arrived at. With the varying spiral and this new scrambler, many experiments were conducted on various aspects like bandwidth, noise and data transmission etc. The details and results are given below.

4.4.1 Better Scrambler Design

Referring to section 3.3, the design basis for the scrambler used until now is that, the entire color plane must be split into 20 small areas for tolerating 5% noise. For the new scrambler, the design is based on an important aspect. As already mentioned in section 2.1, the entire color plane is split into six color regions. Therefore, it is preferable to split it into respective six small areas. Hence the noisy signal will be confined within the respective color area. Additionally, within this "small area", there must be further sub-divisions to have "very small areas" within every "small area" so that the noise tolerance will be further enhanced.

4.4.2 Saturation Scrambler with L=7

The choice of L=7, is for localizing the very small areas. The innermost 4 circles of the spiral are grouped for this purpose, and the outer 3 circles are also grouped likewise.

The sequence of alphabet scrambling is given with designation of the regions as a,b,c,d,e and f as shown in Fig. 4.6. Also, as shown in figure, each region is further sub-divided as (a_1, a_2, a_3); (b_1, b_2, b_3); and so on (only for the outer 3 circles of the spiral). By "$1a_3$" we mean that "segment a_3 in circle number 1 of the spiral". The scrambled sequence is

COMPARISON OF IMAGES

ORIGINAL IMAGE PROCESSED IMAGE

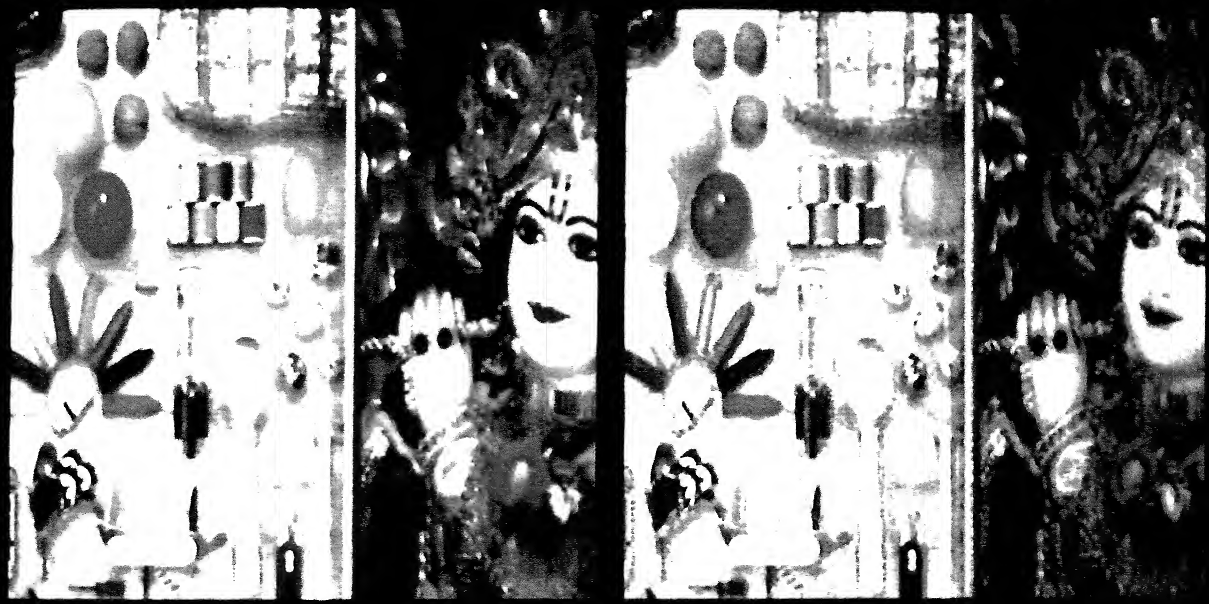


PLATE - 4, [L = 7, SCRAMBLER : 6 areas], S_angle = 36.73 deg

[VARYING SPIRAL], FILTERING : Y = 4.3Mhz, Xvs = 1.3Mhz.

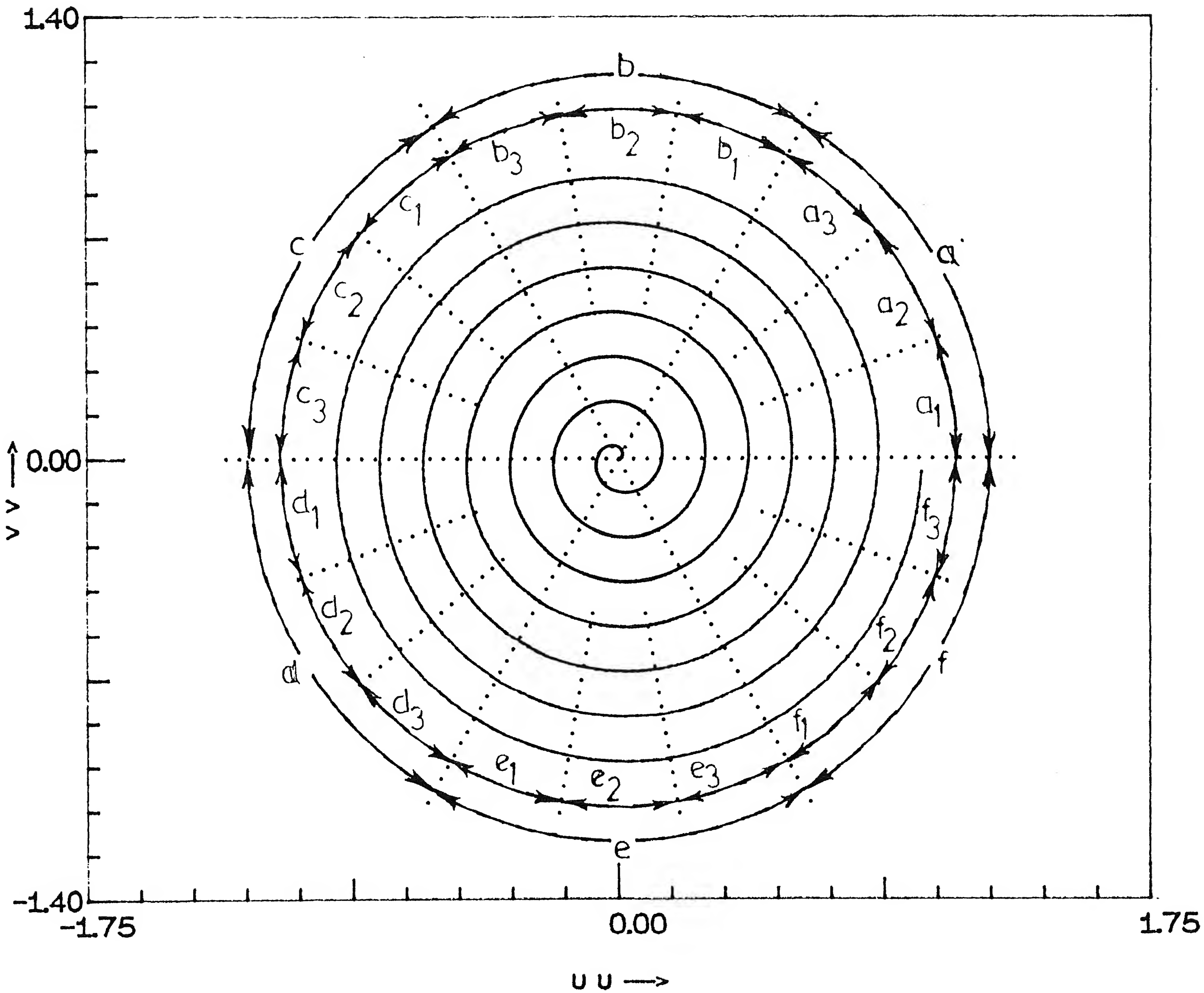


Fig.4.6 Saturation scrambler with L = 7

$$\left[\left\{(1a, -2a, 3a, -4a)(5a_1, -6a_1, 7a_1)(7a_2 -6a_2, 5a_2)(5a_3 -6a_3, 7a_3)\right\}\right.$$
$$\left\{(7b_1, -6b_1, 5b_1)(5b_2, -6b_2, 7b_2)(7b_3, -6b_3, 5b_3)(-4b, 3b, -2b, 1b)\right\}$$
$$\left. \ldots\ldots \right] \quad \text{- for reverse direction signal movement.}$$

As can be observed in the sequence within { } braces, small areas a,b,c,d,e and f are covered. Within each { }, there are 4 very small areas.

For the area `a', the signal value starts at origin. after covering the area `a', it ends at the outer circle (the last point of $7a_3$). In short, area `a' is spanned from (IN ⟶ OUT). The area `b' is covered from (OUT ⟶ IN), starting at the outer circle (the first point of $7b_1$), ends at inner circle (last point of 1b). Similarly the other areas c,d,e and f are also covered in the zig-zag manner swinging from (IN ⟶ OUT) and (OUT ⟶ IN), thus covering the full spiral.

Plate-4 shows the outcome due to this scrambler. The image is ASHISH-IMG. The Y signal is filtered with 4.3 MHz filter, and X_{vs} signal is filtered with 1.3 MHz filter (X_{vs} ⟶ "Squared varying spiral" new signal). The filters are used at both sending end and at receiving end. The S-angle at which better results are obtained with this scrambler is 0.641 radians. The output quality has certainly improved but an overall slight red shade is observed in the entire processed image.

4.4.3 Saturation Scrambler with L=3

With the varying spiral, even an L value of 3 can be used, and therefore, the scrambler with L=3 is designed as before.

The scrambled sequence with L=3 is

$$\left[\left\{1a, -2a, 3a\right\}\left\{3b, -2b, 1b\right\}\left\{1c, -2c, 3c\right\}\left\{3d, -2d, 1d\right\}\right.$$
$$\left.\left\{1e, -2e, 3e)\right\}\left\{3f, -3f, 1f)\right\}\right]$$

To our surprise, the result of this experiment is very much comparable to that of the previous experiment. The Plate-5 shows the result with S-angle and all other processings similar to the above experiment. Due to low L value some color distortion can be observed if viewed carefully.

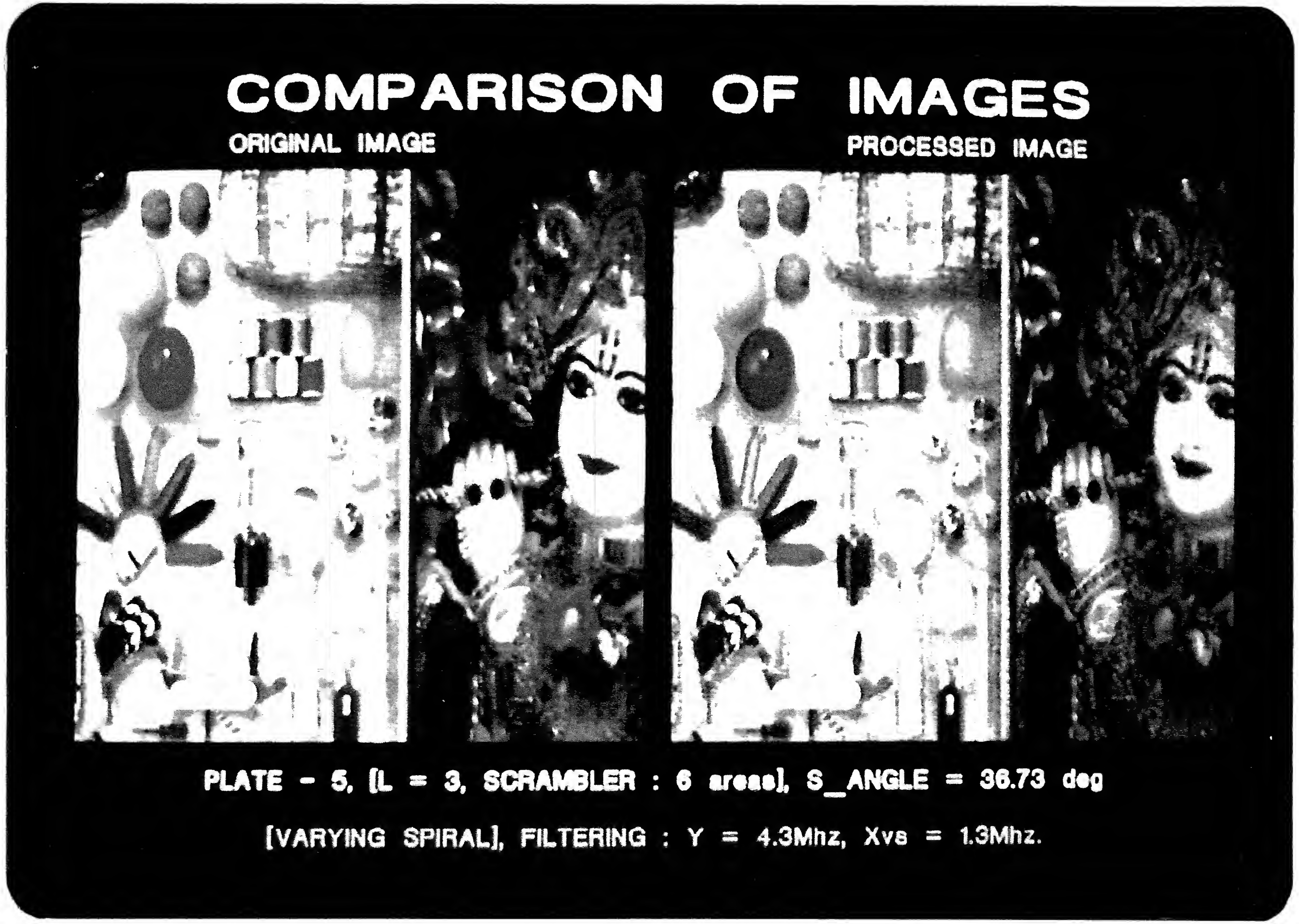
4.4.4 Modulo Property of Saturation Scramblers

The advantage of the above scramblers does not just end with splitting the areas according to color regions. Also, they give the modulo property for the scrambled signal. That is, although the signal range is normalized due to filtering and noise, the signal swings above 1.0 and below 0.0.

On observing the new scramblers we can find that, as the scrambled signal starts in area \`a' at first point of 1a, the signal ends in area 1f' at last point of 1f. For restarting the spiral from the last point of 1f, once again it can start at the first point of 1a. Similarly to go backward from the first point of 1a, it can go to last point of 1f and travel backward. In other words, the signal values, 1.05 is nothing but Mod 1(1.05) = 0.05 and -0.06 is nothing but Mod 1(-0.06) = 0.94. This property can be utilized for better filtering (modulo filtering), and overflow/underflow of signals.

4.4.5 Final Scrambler

With the results of all the three scramblers (although the results of last two are very much comparable), the saturation scrambler with L=7 is finally chosen for the rest of the experiments. Because the varying spiral with L value of \`7', gives wide range of colors. Also, the quality of the chosen scrambler is better among all the three scramblers.(Plate-3, 4 and 5 are the results of these three scramblers for the same image).

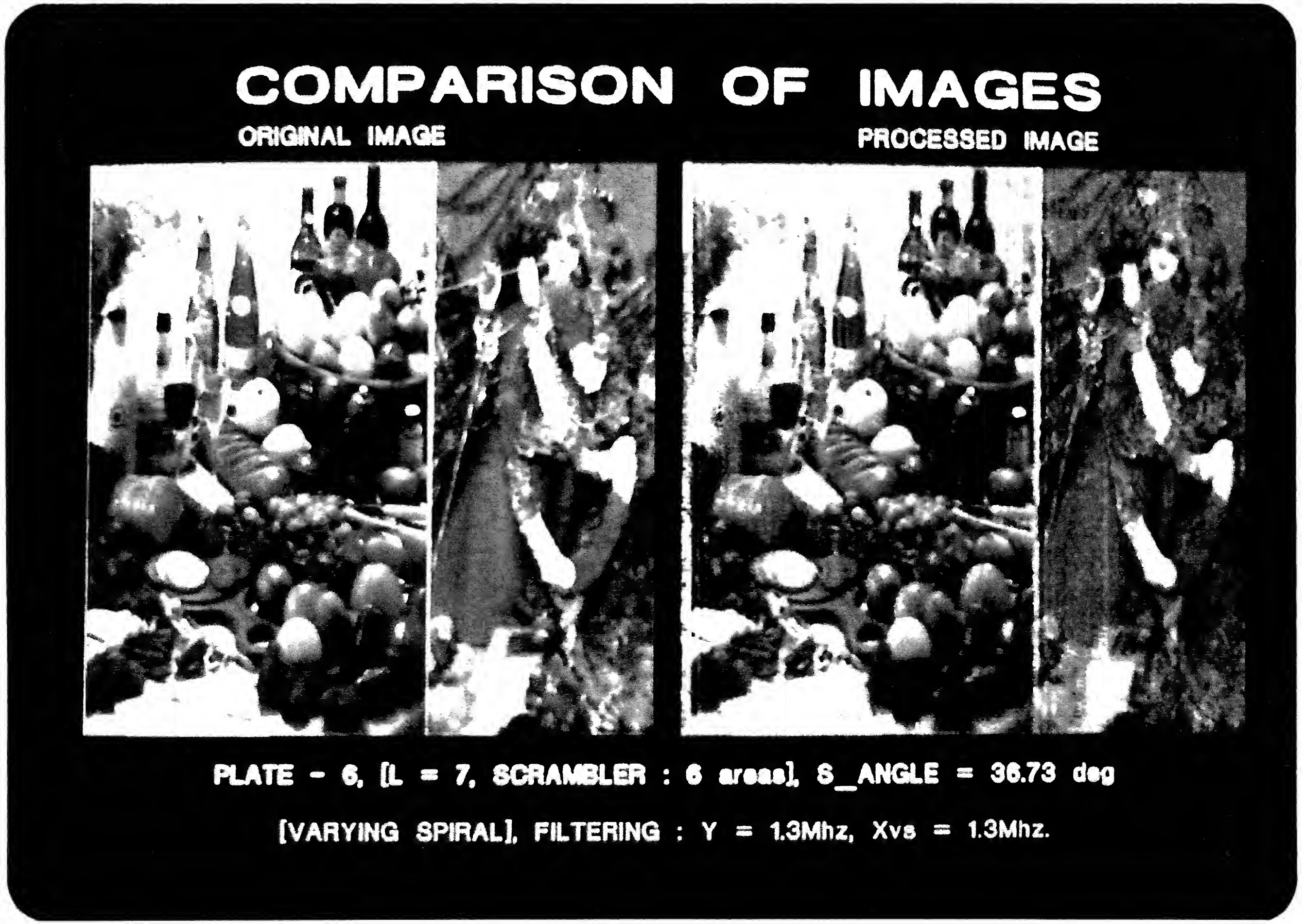

COMPARISON OF IMAGES
ORIGINAL IMAGE
PROCESSED IMAGE
PLATE - 5, [L = 3, SCRAMBLER : 6 areas], S_ANGLE = 36.73 deg
[VARYING SPIRAL], FILTERING : Y = 4.3Mhz, Xvs = 1.3Mhz.

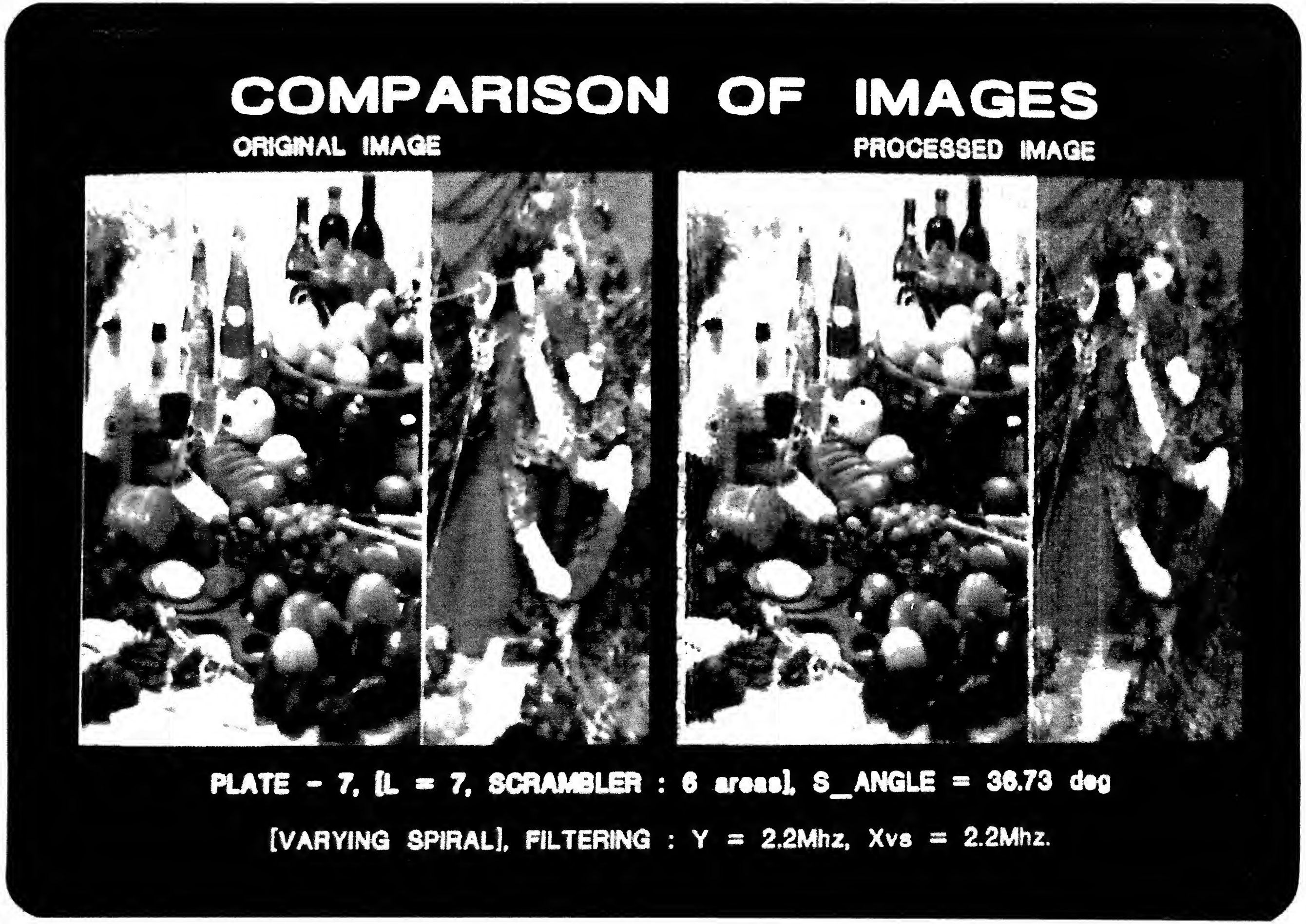
4.4.6 Bandwidth and Noise Experiments

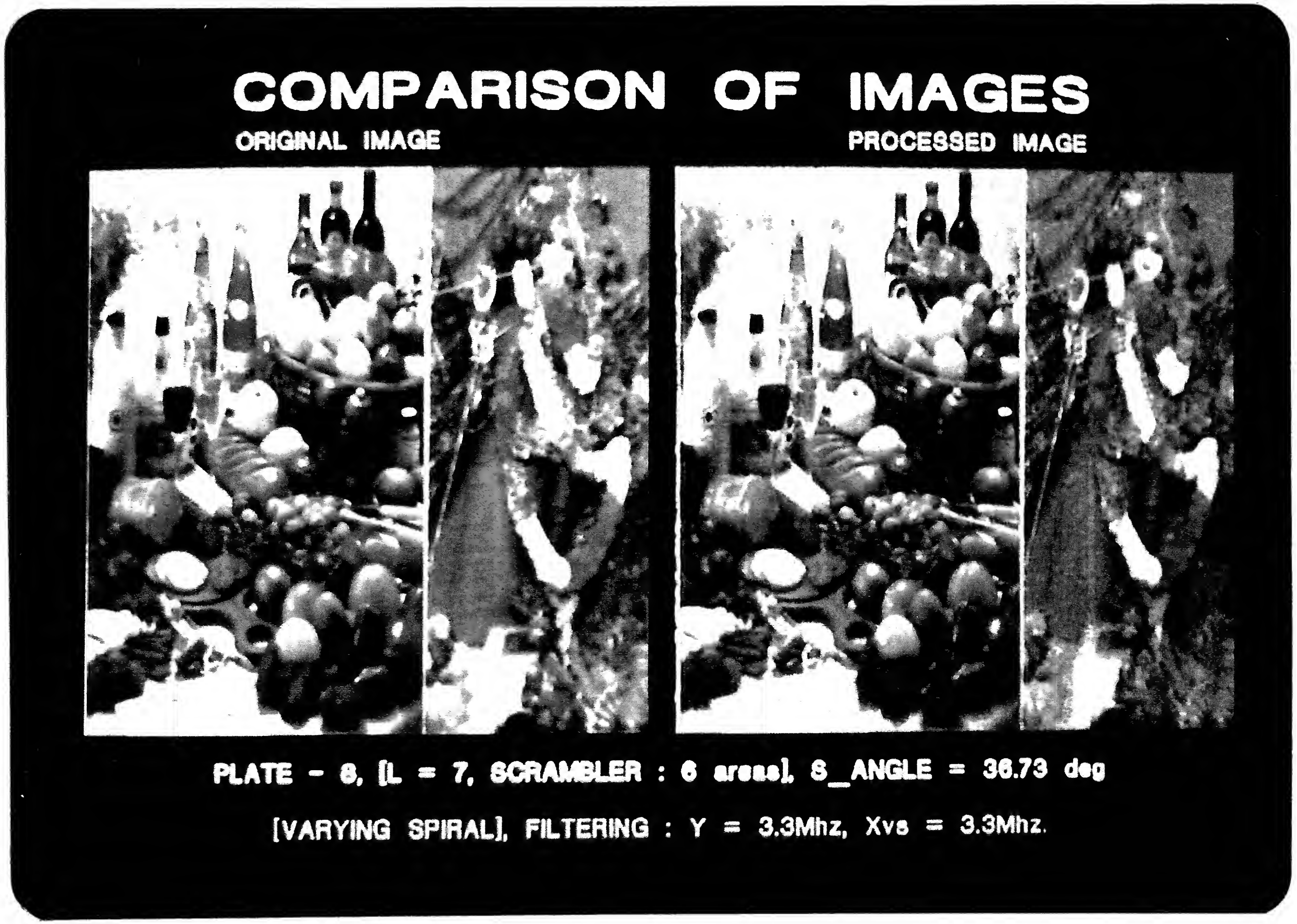
The processing sequence for the experiments of this section are, 1) the varying spiral approximation, 2) squaring 3) scrambling with the final scrambler (L=7). Also the other important factor considered for the experiments done here is that since the signals that we need to transmit are only two i.e. Y and X_{vs} (instead of the usual three - Y, U and V), we can afford to have the full bandwidth for both the signals using QAM techniques at the carrier itself. Therefore for all the experiments of this section, both the signals (Y and X_{vs}) are allowed equal bandwidth.

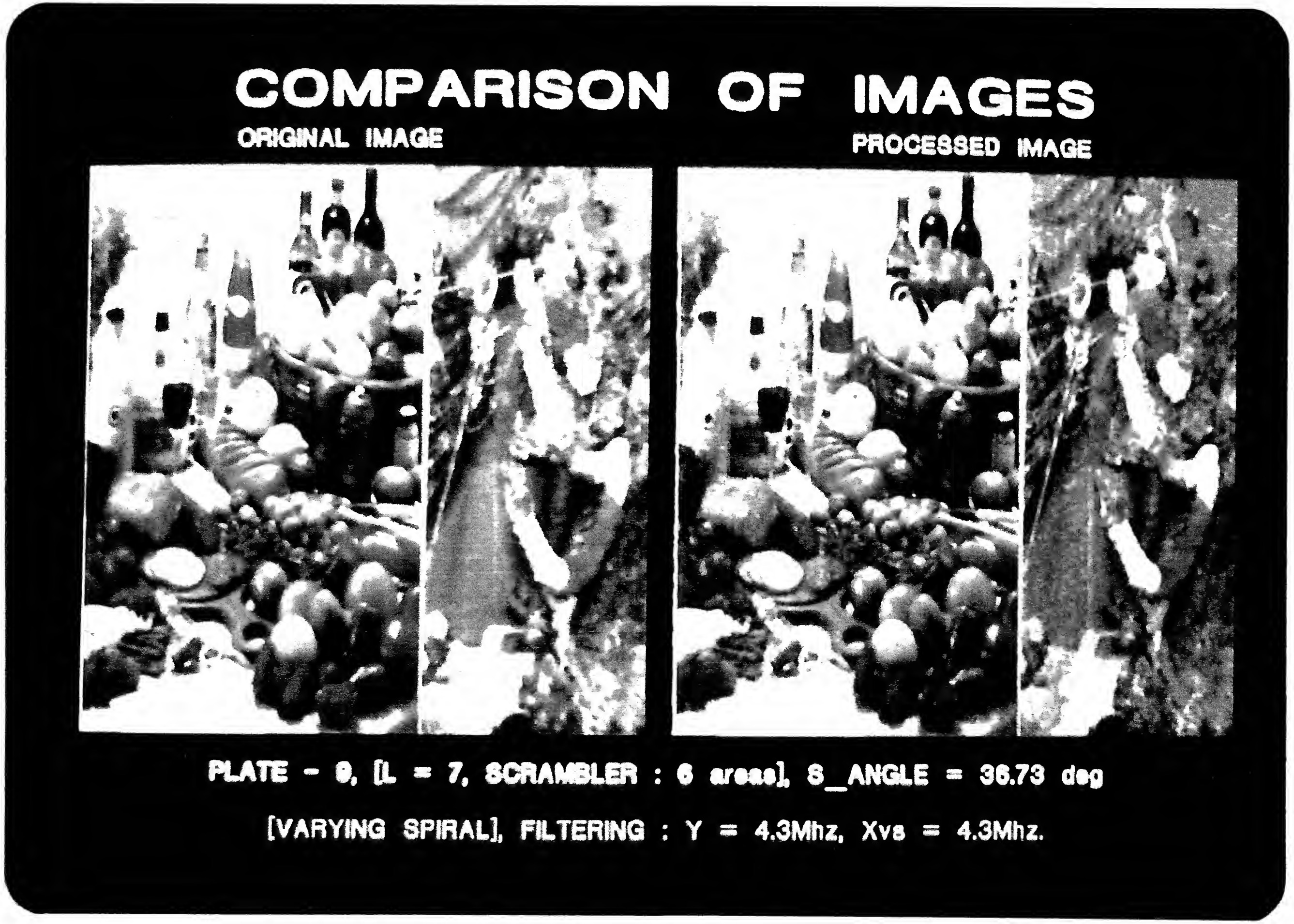
Plates - 6,7,8 and 9 show the results of different bandwidths at 1.3 MHz, 2.2 MHz, 3.3 MHz and 4.3 MHz respectively, for first-img with S-angle = 0.641 rad. As can be observed from the photographs, the quality steadily improves as the bandwidth is increased. With the maximum bandwidth (for the TV transmission) 4.3 MHz, the result is certainly significant.

Plate-10, shows the results of actual transmission test, by adding white Gaussian noise. The noise variance used for this test is 0.05. Due to the assumption of QAM for Y and X_{vs}, the noise will be considered as in phase and quadrature components, (To obtain this 0.05 will be multiplied by 0.707, which equals 0.03535) because any one component of noise only can affect, either Y or X_{vs}. The signal to noise ratio (SNR) for Y signal is 9.0 db and X_{vs} signal is 13.0 db As seen in the Plate-10, this (practically) maximum amount of noise, has not deteriorated the quality of the image to any great extent. Also seen are the dithering effects due to noise, which has improved the quality for certain objects of the image. The specifications are S-angle = 0.641 rad. Other processing parameters being same, bandwidth is 4.3 MHz for both signals and the image in Plate-10 can be conveniently compared with noiseless (filtered) image in Plate-9.


COMPARISON OF IMAGES
ORIGINAL IMAGE
PROCESSED IMAGE
PLATE - 6, [L = 7, SCRAMBLER : 6 areas], S_ANGLE = 36.73 deg
[VARYING SPIRAL], FILTERING : Y = 1.3Mhz, Xvs = 1.3Mhz.


COMPARISON OF IMAGES
ORIGINAL IMAGE
PROCESSED IMAGE
PLATE - 7, [L = 7, SCRAMBLER : 6 areas], S_ANGLE = 36.73 deg
[VARYING SPIRAL], FILTERING : Y = 2.2Mhz, Xvs = 2.2Mhz.


COMPARISON OF IMAGES
ORIGINAL IMAGE
PROCESSED IMAGE
PLATE - 8, [L = 7, SCRAMBLER : 6 areas], S_ANGLE = 36.73 deg
[VARYING SPIRAL], FILTERING : Y = 3.3Mhz, Xvs = 3.3Mhz.


COMPARISON OF IMAGES
ORIGINAL IMAGE
PROCESSED IMAGE
PLATE - 9, [L = 7, SCRAMBLER : 6 areas], S_ANGLE = 36.73 deg
[VARYING SPIRAL], FILTERING : Y = 4.3Mhz, Xvs = 4.3Mhz.


COMPARISON OF IMAGES
ORIGINAL IMAGE
PROCESSED IMAGE
PLATE - 10, [L = 7, SCRAMBLER : 6 areas], S_ANGLE = 36.73 deg, VARYING SPIRAL
FILTERING : Y = 4.3Mhz, Xvs = 4.3Mhz; SNR : Y = 9.0db, Xvs = 13.0db.

4.4.7 Experiments for Data Transmission of New Signal

In this section, the effect of quantizing the new signal for digital storage/transmission is studied. Some relevant information about the existing systems are also included. In the existing system, for Y, U and V signals the number of bits used are 8, 4 and 4 respectively. For the signals (U and V with which we operate), totally 8 bits are used (4 for each U and V). For any change in the number of bits for these signals, the change will have to be made for both U and V signals i.e. when we increase from 4 bits to 5 bits, totally there will be 10 bits (5 for each U and V). Hence we can alter the bits only in steps of 2, as there are actually two signals.

But with the new signal X_v, which was obtained by combining the two signals, we can change the number of bits in integer steps i.e. one can have 3,4,5,6,7 or any desired number of bits for the new signal X_v, which is basically a combination of the two signals U and V.

For the existing system i.e. with 4 bits each for U and V, when the signals are quantized, we will have 16 steps for each signal or 256 points in color plane. In Fig. 4.7, these 256 points are shown in the color plane, for Y values at 0.2, 0.4, 0.6 and 0.8 with varying color gamut also. As can be noticed, most of the points (more than 80%) lie outside the actual color gamut, for some Y values. Due to this, not only the bits are not efficiently utilized, also, there are less number of useful points in the actual gamut.

Due to varying spiral, when the new signal X_v is quantized, for all values of Y, the given number of bits or the given number of color points are almost completely used within the actual gamut, as shown by crowded points inside the varying gamut, in Fig. 4.7. Therefore, the new signal can be quatized with less number of bits (than needed for both U and V). Since all the points are always within the color gamut, more color ranges are also obtained with less number of bits.

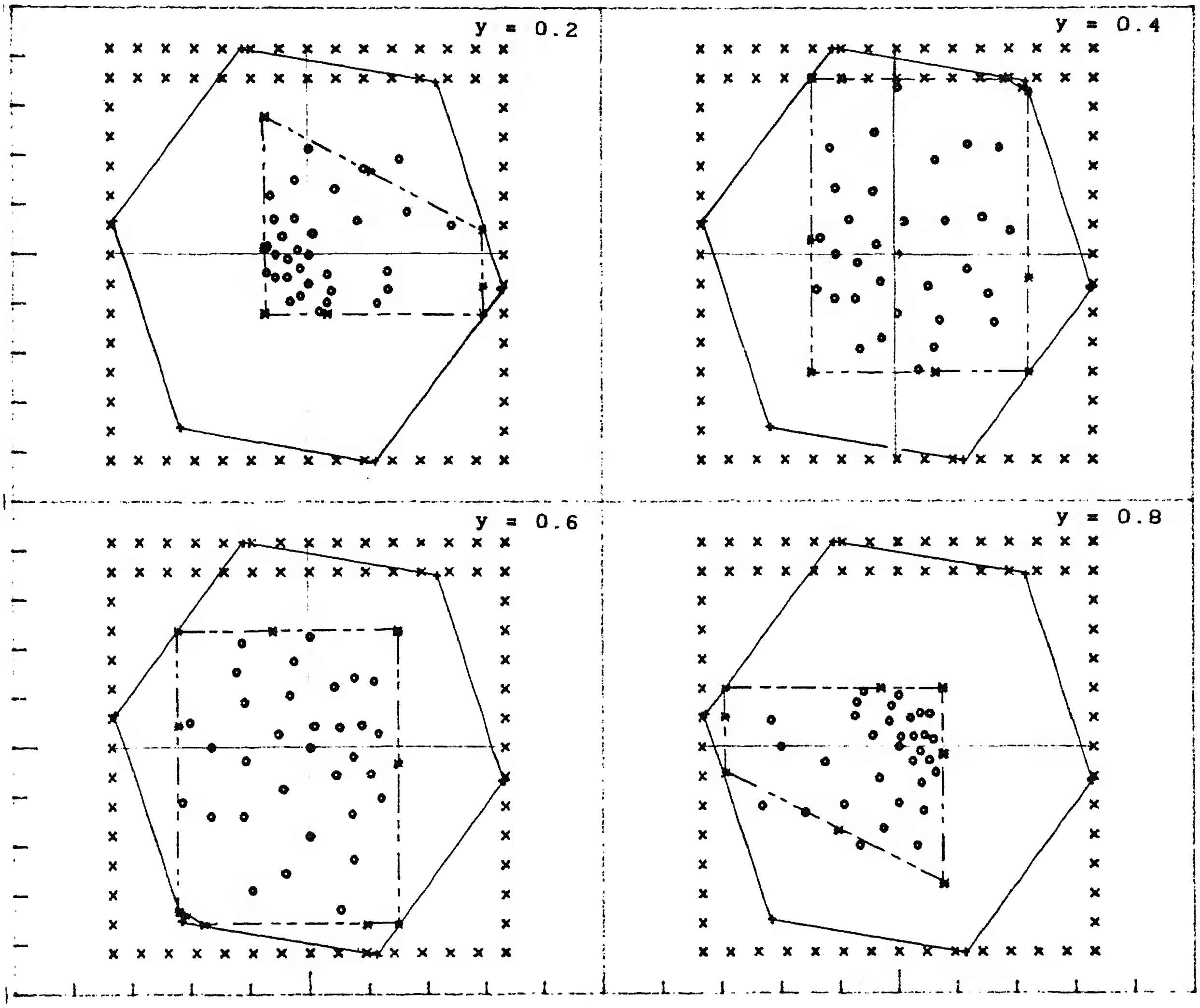


Fig.4.7 Quantization points on color plane
o — 5 bits for X_{vs} signal x — 4 bits each for U/V signals

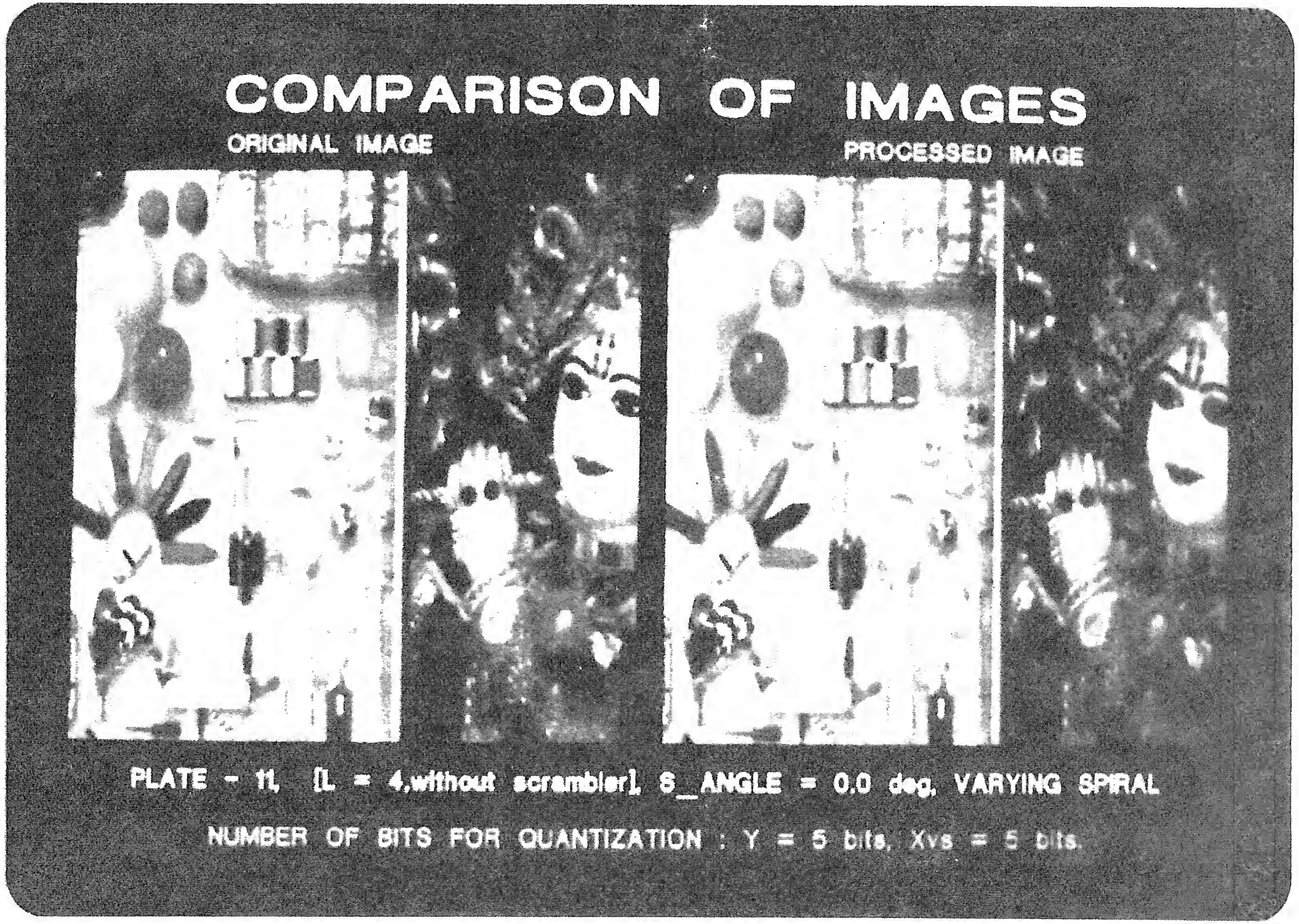
Experiments revealed that for (varying spiral) L=4 and number of bits for X_v signal equals to 5, an excellent quality was observed. Below 5 bits, however the possible color ranges are very much reduced (<= 16 points), leading to noticeable approximation. Plates-11 and 12, show these outputs for ASHISH-IMG, and the high frequency contained BABOON-IMG.

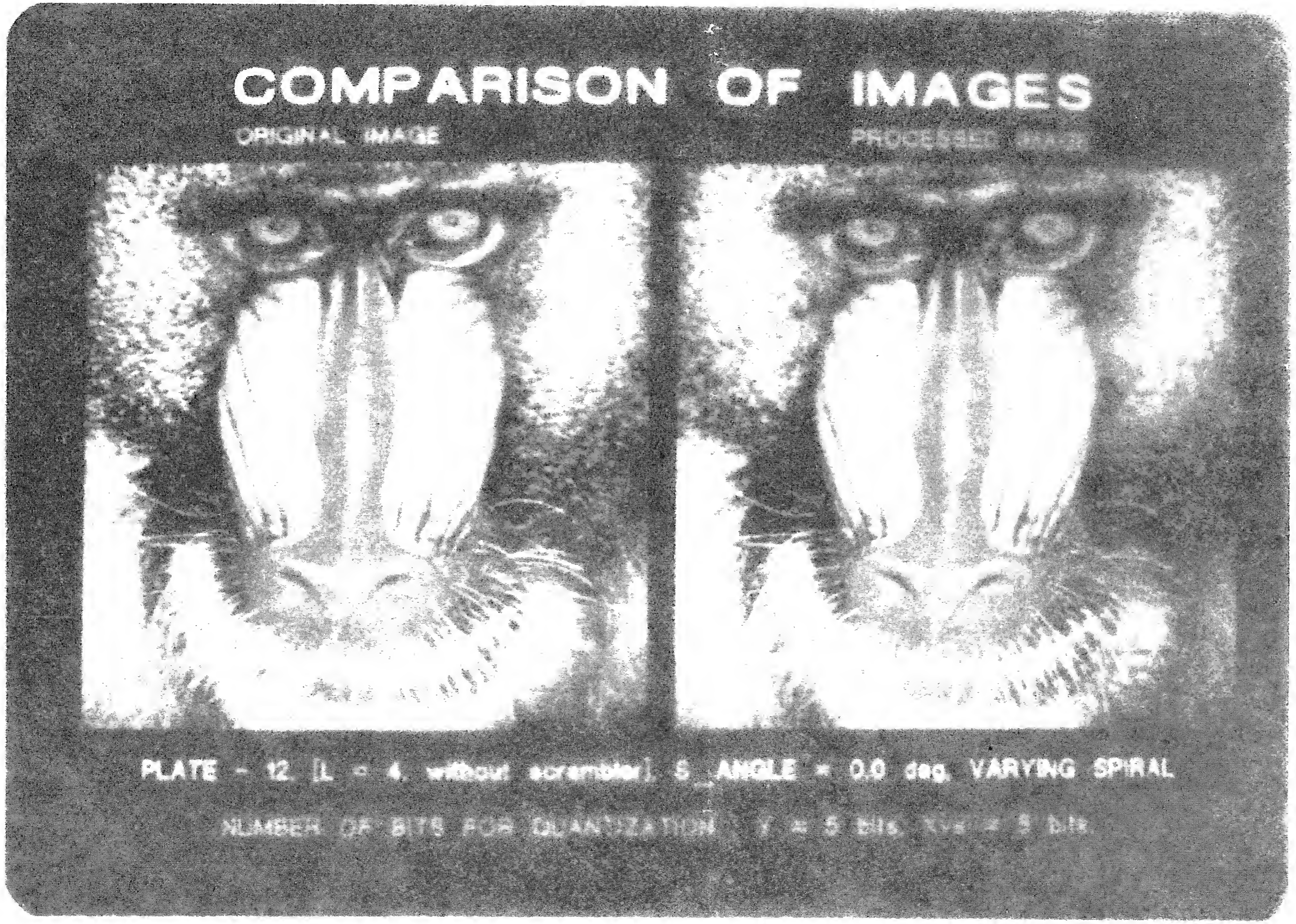
The specifications are S-angle = 0.0 rad. & L=4.

Number of bits for X_v signal = 5

Number of bits for Y signal = 5.

Instead of usual 8 bits quantization for Y, the minimum possible 5


COMPARISON OF IMAGES
ORIGINAL IMAGE
PROCESSED IMAGE
PLATE - 11, [L = 4,without scrambler], S_ANGLE = 0.0 deg, VARYING SPIRAL
NUMBER OF BITS FOR QUANTIZATION : Y = 5 bits, Xvs = 5 bits.


COMPARISON OF IMAGES
ORIGINAL IMAGE
PROCESSED
PLATE - 12. [L = 4, without scrambler], S_ANGLE = 0.0 deg. VARYING SPIRAL
NUMBER OF BITS FOR QUANTIZATION : Y = 5 bits,

CHAPTER - 5

CONCLUSION AND SUGGESTIONS FOR FURTHER WORK

5.1 CONCLUSION

From the results of the many experiments, the following are the overall observations/explanations arrived at finally.

	Observation	Explanations
a)	Simple and varying spiral approximation	Their validity is proved beyond doubt. (The nature of variation for the varying spiral can be adjusted, if required).
b)	Calculation of L value from the JND concept (= 40) and the practically required very low L value (= 6)	The test environment for finding JND ellipses are very strict, i.e. in the full field of vision, there will be only two colors for matching. However, practically such a hypothetical scene never occurs and always there are mixture/combination of many spectral colors due to many objects and hence high value of L is not practically required.
c)	Problems with band-limiting the new signal	The serious problems are due to the fluctuation of signal values around the actual value. When such fluctuation gives false red colors, the quality of the output image deteriorates, because the eye is most sensitive for red colors.
d)	Scramblers and their inadequate performance	Although, without the scrambler, no result can be claimed in this work, even the better design (saturation scrambler with L=7) used here is not optimal.
e)	Quantization of new signal for data transmission	This is certainly a proved result. It's success relies on the effective use of the given number of bits for the new signal, throughout the Y values. It was possible, by the deep study of signal space analysis in the Y, U, V domain.

In short, the overall conclusions are,

1) The two chroma signals can be very profitably combined into single signal, and two channel color system is a viable alternative. This has immediate relevance for data compression possibilities.

2) Admittedly, further improvement is possible. The initial thrust obtained from the results of spiral approximation, more than justify further investigation.

5.2 SUGGESTIONS FOR FURTHER WORK

There are many investigations that can be done in continuation of this work.

i) Very importantly, either an optimal scrambler or some other suitable technique similar to scrambler can be developed. The most important requirement of such a technique is that the additional red color points generated due to filtering must be minimized.

ii) With the scrambler discussed here, the modulo property can be well utilized and therefore larger signal swings (more than half the dynamic range), can be totally avoided. This would result in creating less number of false colors and therefore less red false colors also.

iii) Other than the spiral, polygon (Hexagon or Pentagon) approximation can be done whose structure can also vary along Y, like varying spiral. The advantage in such a system is that the colors missed at the sharp edges due to curved spiral approximation, can also be reproduced and therefore color ranges will increase, and color approximation for the pure colors will be better. The results of such a polygon approximation will not be very much different than the results due to spiral approximation, because basically the signal domain is very much redundant and flexible.

iv) Since the choice of primaries can influence the structure of our signal space to a great extent, further possibilities may be explored, by suitably selecting new primaries and efficient implementation of these techniques may be investigated.

V) After combining the chroma signals, effectively we have two signals, "Y and X_{vs}". Using the same principles, these two signals can once again be combined to ultimately have only one signal for color TV applications.

vi) Otherwise, the works of LAND i.e. two primaries system for full colors, can be invoked again and the two signals of LAND can be combined using this principle to ultimately have single signal.

vii) For all the evolving systems like, Digital Television, HDTV, Videophone, Teleconferencing, etc, this technique can be extended for simple and efficient system design.

REFERENCES

[1] Macadam D.L., "Color Measurement - Theme and Variations", Springer Verlag, New York, 1981, p 1, p 11 & p 201.

[2] Harry A.C., "Handbook of Colorimetry", Technology Press, Cambridge, Mass., 1936.

[3] Knox Mcilwain, E.E. Charles E. Dean, "Principles of Color Television", John Wiley & Sons, NY, 1956, p 22, p50, p 53 & p 64.

[4] Hunt R.W.G., "The Reproduction of Color" IV Edition, Fountain Press, England, 1987, p 73.

[5] Pearson D.E., "Transmission and Display of Pictorial Information", Pentech Press, London, 1975, p 162, p 176.

[6] Macadam D.L., "Visual Sensitivities to Color Differences in Day Light", Jr. of the Optical Society of America, Vol. 32, May 1942, p 247.

[7] Macadam, D.L., "Specification of Small Chromaticity Diffe- rences ", JOSA, Vol. 33, Jan. 1943, p 18.

[8] Land E.H., Proc. Natl. Acad. Aci. 45, 115, 636 (1959), Proc. of Physics, Vol. 45, 1959, p 115.

[9] Agoston G.A., "Color Theory and its Application in Art and Design", Springer Verlag, New York, 1979, p 65, p 58.

[10] Gulati, R.R., "Monochrome and Color Television", Wiley Eastern Limited, 1988, p 546, p 591.

[11] Embree Paul M., Kimble B., "C Language Algorithms for Digital Signal Processing", Prentice Hall, NJ, 1991.

APPENDIX - A

TRANSFORMATION MATRICES

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.299 & -0.587 & -0.886 \\ 0.701 & -0.587 & -0.114 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.0 & 0.0 & 1.0 \\ 1.0 & -0.194208 & -0.50937 \\ 1.0 & 1.0 & 0.0 \end{bmatrix} \begin{bmatrix} Y \\ U \\ V \end{bmatrix}$$

$$\begin{bmatrix} Y \\ UU \\ VV \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.332222 & -0.652222 & 0.984444 \\ 1.001429 & -0.238571 & -0.162857 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 1.0 & 0.0 & 0.7 \\ 1.0 & -0.174787 & -0.356559 \\ 1.0 & 0.9 & 0.0 \end{bmatrix} \begin{bmatrix} Y \\ UU \\ VV \end{bmatrix}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.607 & 0.174 & 0.2 \\ 0.299 & 0.587 & 0.114 \\ 0.0 & 0.066 & 0.111 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.909 & -0.532 & -0.288 \\ -0.985 & 1.997 & -0.028 \\ 0.058 & -0.119 & 0.902 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & 0.9 & 0.0 \\ 0.0 & 0.0 & 0.7 \end{bmatrix} \begin{bmatrix} Y \\ UU \\ VV \end{bmatrix}$$

$$\begin{bmatrix} Y \\ UU \\ VV \end{bmatrix} = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & 1.111111 & 0.0 \\ 0.0 & 0.0 & 1.428571 \end{bmatrix} \begin{bmatrix} Y \\ U \\ V \end{bmatrix}$$

$$\begin{bmatrix} Y \\ UU \\ VV \end{bmatrix} = \begin{bmatrix} 0.0 & 1.0 & 0.0 \\ 0.064980 & -1.243027 & 1.001938 \\ 2.729104 & -2.191097 & -0.413045 \end{bmatrix} \begin{bmatrix} Y \\ UU \\ VV \end{bmatrix}$$

APPENDIX - B

FILTER: SPECIFICATION AND CONSTANTS

FILTER-1

IIR - LPF

Samping frequency = 10.0 MHz

Passband frequency = 1.3 MHz , Stopband frequency = 2.3 MHz

Passband ripple = 0.1 db , Stopband ripple = 30.0 db

4th ORDER ELLIPTIC FILTER.

Number of sections = 2

K = 0.03433381 (gain)

Section - 1

$B_1 = 1.302002$, $B_2 = 1.0$, $A_1 = -1.0057983$, $A_2 = 0.3250351$

Section - 2

$B_1 = -0.11277771$, $B_2 = 1.0$, $A_1 = -1.0582581$, $A_2 = 0.73622131$

FILTER-2

IIR - LPF

Sampling frequency = 10.0 MHz

Passband frequency = 2.0 MHz , Stopband frequency = 2.5 MHz

Passband ripple = 0.28 db , Stopband ripple = 40.0 db

5th ORDER ELLIPTIC FILTER.

Number of sections = 3

K = 0.0552961603 (gain)

Section - 1

$B_1 = 1.0$, $B_2 = 0.0$, $A_1 = 0.0552961603$, $A_2 = 0.0$

Section - 2

$B_1 = 0.7039934993$, $B_2 = 1.0$, $A_1 = -0.5233039260$, $A_2 = 0.8604439497$

Section - 3

$B_1 = -0.0103216320$, $B_2 = 1.0$, $A_1 = -0.6965782046$, $A_2 = 0.486009932$

FILTER - 3

IIR - LPF

Sampling frequency = 10.0 MHz

Passband frequency = 3.0 MHz , Stopband frequency = 4.0 MHz

Passband ripple = 0.1 db , Stopband ripple = 30.0 db

4th ORDER ELLIPTIC FILTER

Number of sections = 2

k = 0.21335123 (gain)

Section - 1

B_1 = 1.9332275, B_2 = 1.0, A_1 = 0.16523361, A_2 = 0.12421799

Section - 2

B_1 = 1.6645203, B_2 = 1.0, A_1 = 0.71719360, A_2 = 0.69523621

FILTER - 4

IIR - LPF

Sampling frequency = 10.0 MHz

Passband frequency = 4.0 MHz , Stopband frequency = 4.8 MHz

Passband ripple = 0.1 db , Stopband ripple = 30.0 db

4th ORDER ELLIPTIC FILTER

Number of sections = 2

k = 0.45204118

Section - 1

B_1 = 1.9976196, B_2 = 1.0, A_1 = 0.91645813, A_2 = 0.28045654

Section - 2

B_1 = 1.9864807, B_2 = 1.0, A_1 = 1.52639770, A_2 = 0.79066467